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Fish Passage Investigations at the Hiram M. Chittenden Locks, Seattle, WA in 2000

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
cubic feet / second (cfs)	0.0283	cubic meters / second

Preface

The report herein was prepared by the Fisheries Engineering Team (FET), Water Quality and Contaminant Modeling Branch (WQCMB), Environmental Processes and Effects Division (EPED), Environmental Laboratory (EL), U.S. Army Engineer Research and Development Center, Waterways Experiment Station (WES) with support from the AScI Corporation, 1365 Beverly Road, McLean, VA 22101, U.S. Army Engineer, Seattle District Environmental Resources Section, and MEVATEC Corp., 1525 Perimeter Parkway, Huntsville, AL 35806. The report was prepared by Messrs. Peter N. Johnson (FET), Frederick A. Goetz (USACE Seattle), Michael E. Hanks (FET) and Gene R. Ploskey (FET) and was conducted under the general supervision of Dr. Mark Dortch, Chief, WQCMB; Dr. Richard Price, Chief, EPED; and Dr. John Harrison, Chief, EL.

Many people made valuable contributions to this study, especially the personnel at the Hiram M. Chittenden Locks. John Post (Project Manager) and Bill Livermore (Chief of Maintenance) provided generous support and expertise with logistical and troubleshooting issues. Jim Kragstaedt and Dave Murray (mechanics) help with the design and deployment of transducer mounts. Patricia Pearson and Gina White (Shoreline Community College) visually counted smolt passing over the flumes. Charles Ebel (USACE Seattle) also helped with fish counting and with transducer deployment. Carl Schilt (FET) edited an earlier version of this report.

Funding for this study was provided by Seattle District through two USACE authorities (studies) the Lake Washington General Investigation Study (GI) and the Lake Washington Ship Canal Section 1135 Smolt Passage Improvement Project. These studies could not have been completed without the patience, determination and enthusiasm of the Project Manager, Linda Smith. These studies include local contribution through local sponsorship, with King County and the City of Seattle as the primary sponsor under both programs and the Muckleshoot Tribe providing funding for the 1135 Project. John Lombard, King County Land and Water Resources, Doug Houck, King County METRO, and Keith Kurko, City of Seattle, provided the major effort and support in gathering the local partnership.

At the time of publication of this report, Acting Director and Commander of WES was COL Robin Cababa, EN.

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Introduction

The Lake Washington system appears to be highly productive, producing nearly the largest salmon smolts (coho, chinook, and sockeye) for their age of any river basin (Weitkamp et al. 1995; Meyers et. al. 1998; Burgner 1991; J. Woodey, UW, unpublished data). Since the mid-1980s, all salmon (chinook, coho, and sockeye) and steelhead runs have been in serious decline in the Lake Washington system. The decline in all Lake Washington anadromous fish runs precipitated resource agency and tribal biologists to investigate conditions at the Hiram M. Chittenden Locks (Locks) to try to identify the potential causes for the declines (WDFW 1996). An outgrowth of agency and tribal investigations was the initiation of two Corps studies, the Lake Washington Ship Canal Section 1135 Smolt Passage Improvement Project (Section 1135 Project) and the Lake Washington General Investigation Study (GI Study).

The Section 1135 Project is considered an adaptive management project based on an ongoing series of experimental actions to improve fish passage for juvenile salmon and steelhead migrating through the project area (WDFW 1996; D. Seiler, WDFW, unpublished data; Goetz et al. 1999; USACE 1999; Johnson et al. 2000). In 2000, as part of the Section 1135 Project, a series of structural and operational changes were made at the Locks – four smolt passage flumes were installed on the spillway, slow fill of the large lock chamber was continued from 1999, barnacles were removed from the large lock filling conduits, and strobe lights were installed around the large lock culvert intakes. The GI study is following (in time) the Section 1135 Project and includes monitoring studies to assess the need for additional water for fish passage at the Locks, and habitat assessment to identify potential restoration opportunities throughout the Lake Washington Basin.

At the Locks, there is a large degree of uncertainty in knowing what past actions in the basin have contributed to the decline in freshwater productivity of Lake Washington anadromous fish stocks. Awareness that the Locks may be either a contributing factor to salmon declines or even a “bottleneck” for juvenile fish passage, was gained through an interactive, iterative process between resource agency biologists and Corps staff using long-term indicators of system health, and specified measurements of existing project operations and controlled or paired evaluations (WDFW 1996; D. Seiler, WDFW, unpublished data; Goetz et al. 1999; USACE 1999; Johnson et al. 2000). The evaluation of that baseline and adaptive monitoring resulted in the current modifications to the Locks through the Section 1135 Project.

For the Section 1135 Project, we have developed restoration and monitoring objectives with explicit hypotheses (described in USACE 1999) to test each major management measure of the recommended restoration plan. The restoration objectives for the LWSC Section 1135 project are:

1. Increasing smolt passage over the spillway.
2. Minimizing smolt entry (entrainment) into the large lock filling conduits.
3. Minimizing smolt injury during passage through the large lock conduits.
4. Minimizing injury and mortality to chinook salmon in conformance with ESA listing of Puget Sound chinook.

The overall objective for monitoring is to verify the effectiveness of each restoration measure and selected combinations of measures. Under the Section 1135 Project, only two years of project monitoring are planned for 2000 and 2001. Monitoring objectives are divided into long-term and short-term groups. The long-term objective for the project is to develop necessary information to manage the Locks adaptively, implementing the Section 1135 Project as an experiment in maximizing the survival of migratory smolts. Short-term objectives include measurement of smolt passage through major pathways at the Locks – smolt passage flumes, spillway gate, and large lock conduits. By individual or combination of elements, short-term monitoring objectives are:

1. *Smolt Passage Flumes*: Determine the fish collection efficiency of each flume, and combination of flumes. Describe fish collection efficiency in comparison to entrainment of smolts into the large lock filling conduits.
2. *Spillway Gate(s):* Determine relative fish passage numbers with and without smolt slide operation. This item was studied under the GI Study in 2000 but is included here for completeness in describing monitoring objectives.
3. *Large Lock Slow Fill Operation*: Determine the greatest reduction in smolt entrainment (into the large lock conduits) at the fastest fill time. Describe smolt entrainment during periods with and without flume operation.
4. *Strobe Lights*: Determine the reduction in smolt entrainment (into the large lock conduits) with lights-on during seasonal and diel periods of operation.
5. *Combined Slow Fill and Strobe Light Operation*: Determine the entrainment rate for strobe lights and slow fill in combination.
6. *Large Lock Filling Conduits*: Determine the injury rate (reduction or non-reduction) for barnacle removal and slow fill, individually and in combination.

In this report, we will present first year monitoring results for objectives 1 and 3. Results for objective 2 are reported in Biosonics (2000). Additional results for objectives 1, 3, and 6 will be contained in an upcoming report Goetz et al. (in prep). Implementation of strobe lights and monitoring for objectives 4 and 5 are in question, the current strobe light equipment has not proven to be reliable under initial operation. Further information will be provided in the final report.

The GI study includes an objective of providing additional improvements in fish passage efficiency at the Locks, primarily through finding additional sources of water (conservation or new supply). In this report we will be presenting first year results of measuring velocity patterns above the Locks. The information on velocity patterns will add to our understanding of changes in fish use at the monitored passage routes.

Methods

Site Location and Description

We conducted all the research reported herein at the Hiram M. Chittenden Locks (Locks), which is located at outlet of the Lake Washington Ship Canal in Seattle, WA (Figure 1), and is hereafter referred to as The Project. The Project primarily functions as a navigation lock for vessels passing between the freshwater Lake Washington system and the salt water of Shilshole Bay and Puget Sound. About 80,000 vessels pass through the project each year, approximately 80% of which is pleasure craft. Secondarily, the project serves to control the water level of Lake Washington.

From north to south, the Locks consist of a large lock, small lock, a spillway, and an adult fish ladder (Figure 2). The large lock chamber is 24.4 m wide by 251.5 m long and accommodates vessels with drafts as deep as 9.1 m. The chamber is divided into upper and lower halves by a miter gate in the middle. The small lock chamber is 9.1 m wide by 45.7 m long and accommodates vessels with drafts as deep as 4.9 m. The head differential from upstream to downstream of the lock chambers varies from 1.8 to 7.9 m depending on the tidal elevation and the level of Lake Washington. Tide levels measured just downstream from the Locks in Shilshole Bay fluctuate about 3.7 m over the course of each tidal cycle. The spillway is 71.6 m long with six 9.8 m wide openings, each capable of passing about 2700 cfs at maximum discharge.

In May 2000, the Corps of Engineers installed four experimental flumes, two each in spillways 4 and 5 (spillways are numbered from north to south) to increase juvenile salmon passage at the spillway. These flumes were designed and built as part of the Lake Washington Ship Canal Section 1135 Smolt Passage Improvement Project. Throughout this report, the flumes will be referred to as flumes 4A, 4B, 5C, and 5B, north to south. Two flumes are of equal size and discharge, 1.2 m width and 130 cfs discharge (at the intake) the other two flumes are incrementally smaller at 0.9 m, 95 cfs, and 0.6 m, 50 cfs. The two flumes in Bay 4 (flumes 4A and 4B) were 0.6 m and 1.2 m wide, respectively. Flumes 5C and 5B were 0.9 m and 1.2 m wide, respectively. All four flumes pass 405 cfs when completely open. The flumes are dewatered to a final outflow of 12, 15, 14, and 15 cfs, respectively. Each flume can be opened or closed independently, thus giving a large range of available flow combinations from 50, 95, 130, 180, 225, 260, 285, 310, 355 and 405 cfs. Further, during reduced flow, flumes can be turned on for selected time periods, such as day vs. night or for selected peak daytime smolt migration periods. The outlet of each flume was fitted with a passive-integrated-transponder (PIT) tag reader (tunnel monitor). DeVries (2000) reports on results from the companion PIT-tag study.

The large lock chamber is filled via two 4.9 m wide by 4.3 m tall openings (Figure 3) to deep culverts in walls on either side of the channel just upstream of the upper miter gates. The culverts route water north and south, respectively, for about 4.5 m before turning westward (90^o angle) and constricting to 2.6-m wide by 4.3-m tall. The culvert continues laterally along the chamber walls before emptying into the chamber through a series of 22 (1.2-m wide by 0.6-m high) filling ports. The chamber is filled by opening three fixed-wheel vertical lift Stoney gate valves located west of the upper miter gates and east of the middle miter gates. The primary technique used to fill the large lock during the course of the study and throughout the smolt migration season was the “intermediate” valve opening procedure, which lasts up to about 10 minutes at average tide for the upper half chamber. However, two other valve-opening procedures were used: the “slow-continuous” and the “graduated”. The slow-continuous and the graduated openings were only performed during days when the Washington Dept. of Fish and Wildlife (WDFW) was purse seining in the large lock chamber. The slow continuous opening procedure results in filling of the lock chamber in about 6 minutes while the graduated opening requires an average of 14 minutes to fill the chamber. At low tide, maximum discharge into each culvert was approximately 2200 cfs and discharges greater than 1800 cfs lasted up to 3 minutes.

Estimating Fish Entrainment

We used two down-looking 6^0 split beam Precision Acoustic Systems (PAS) transducers, one at each wall, to monitor fish presence near and entrainment into culvert entrances (Figure 3). The transducers were originally fitted with acoustic lenses that expanded the effective beam angle to 12^0, but initial testing showed that volume reverberation was a problem, so we removed the lenses for all subsequent sampling. The transducers were deployed out 1.2 m from the wall and 12 m above the lock entrance floor, and were aimed straight down along the centerline of the culverts. The width of each sampling beam at the culvert entrance floor was 1.2 m, or about one quarter of the width of the intake. Spring-hinged mounts allowed for the transducers to be folded back against the wall when the miter gates were opened for boat traffic and repositioned for sampling when the miter gates were closed. We operated the transducers using a 420 kHz PAS 103 Multimode Scientific Sounder, PAS 203 Local Surface Multiplexor, and an ACI 200 MHz personal computer loaded with Hydroacoustic Assessment Research Program (HARP) software and equipped with a data acquisition card. We fast-multiplexed the two transducers at 10 pings per second each. We collected hydroacoustic data for at least 23 hours per day (approximately 1 hour per day lost due to downloading) from 19 May through 7 August. We did not sample with the south wall transducer from 10 –17 July because a transducer mount was broken.

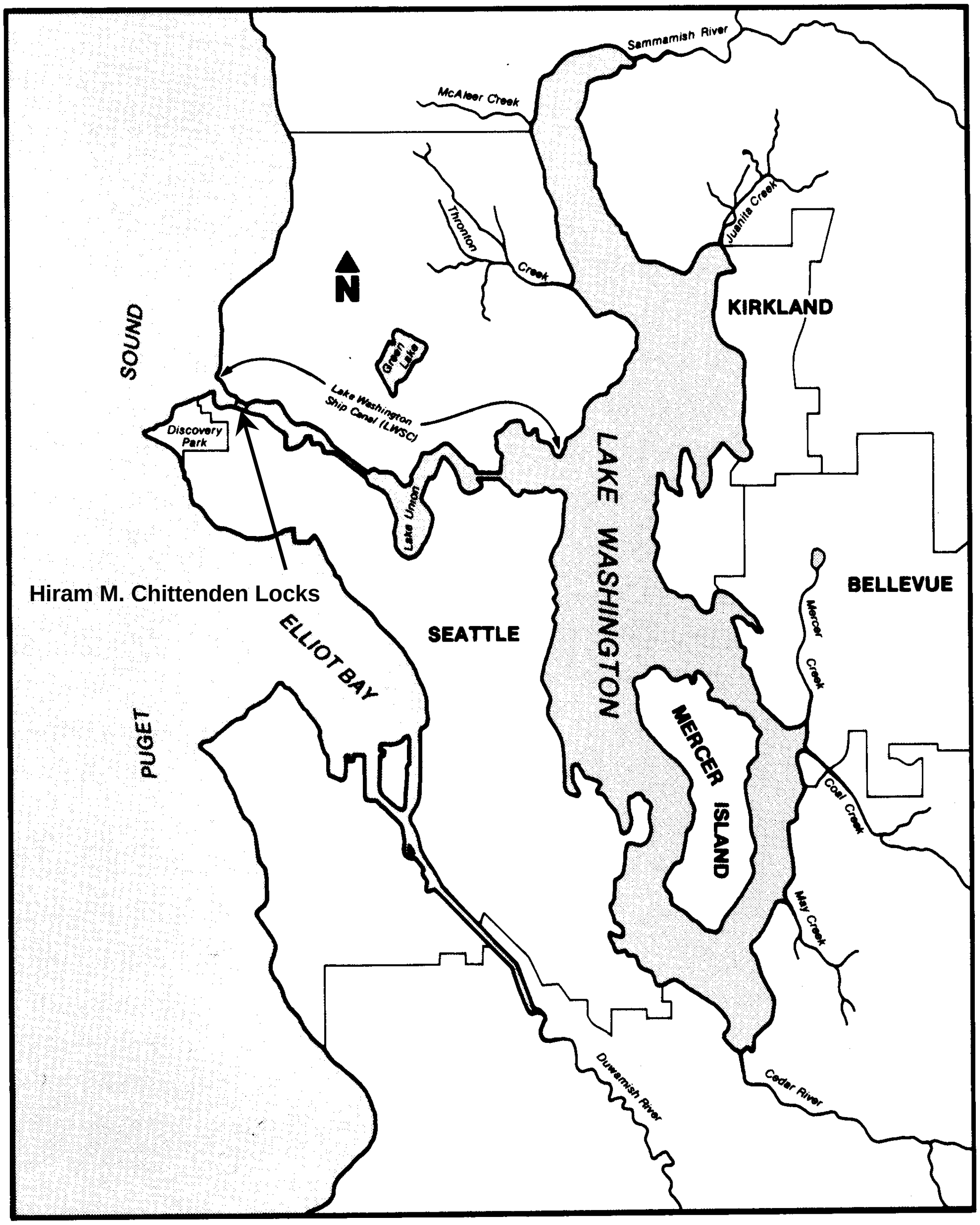

Figure 1. Site map of Lake Washington basin showing the Lake Washington Ship Canal and the location of Hiram M. Chittenden Locks Project.

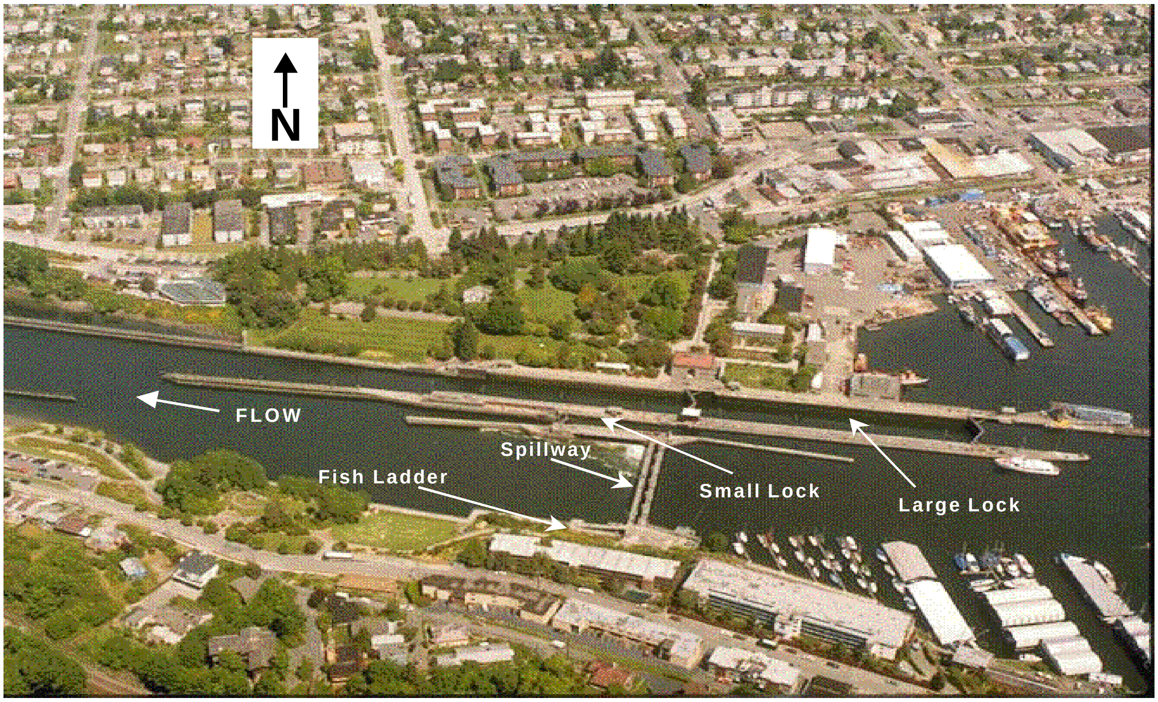

Figure 2. Aerial photograph of the Hiram M. Chittenden Locks Project showing all major structures.

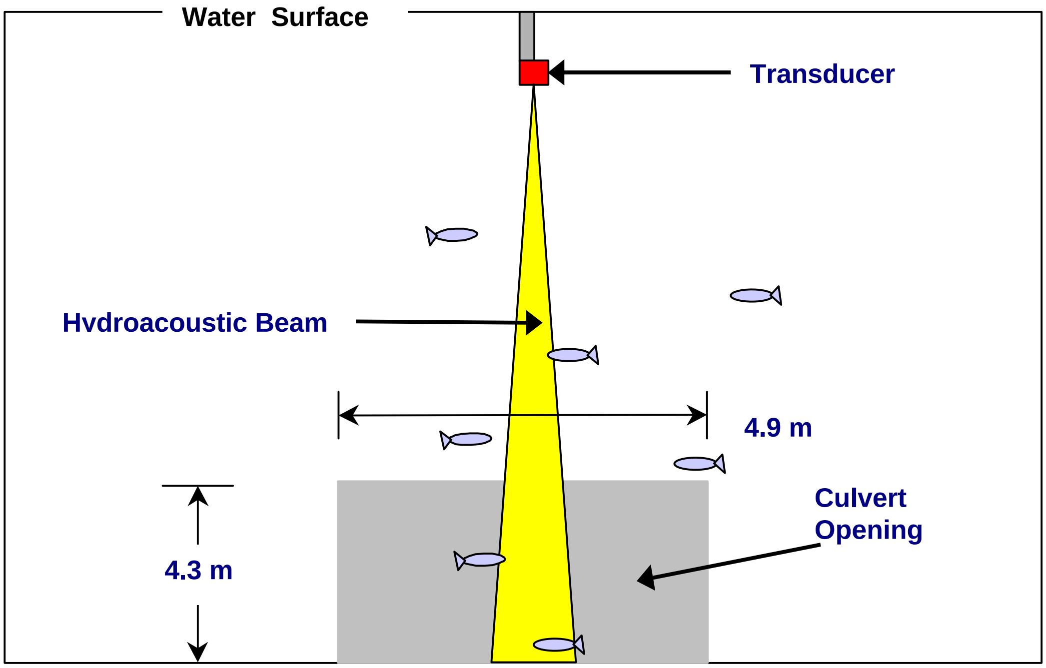

Figure 3. Conceptual diagram of a culvert opening at the Hiram M. Chittenden Locks Project showing the location of the hydroacoustic sampling beam.

Detectability Modeling

Detectability of hydroacoustic sampling is the probability of obtaining adequate numbers of echoes from targets of interest passing through a hydroacoustic beam. A number of factors influence detectability, including acoustic size of fish passing through hydroacoustic beams relative to the threshold for data collection (in this case no targets smaller than –56 dB were collected), range of targets from transducer, acoustic system configurations, and environmental conditions. The output from detectability models are range-specific effective beam angles (EBA's), a primary factor in estimating spatial expansions of detected fish (see below). We derived EBA's for the down-looking transducers using a Monte Carlo simulation model developed by William T. Nagy, USACE Portland District, Fisheries Field Unit. Model parameters and values used are shown in Table 1. Additionally, equations describing relations between fish trace slope and range (Figure 4), and between two way sound pressure level and angle off axis (beam directivity) were part of the model (Figure 5).

Acoustic Data Processing

We processed acquired hydroacoustic data from about 30 minutes prior to and through the end of each fill event from 19 May to 7 August. During that time period, a total of 555 fill events occurred, of which we sampled 550 (99%). There were 142 full chamber fills and the remaining 408 were upper chamber fills. Upper chamber fills were comprised of slow-continuous (n=13), graduated (n=13), or intermediate (n=382) valve-opening procedures. Full chambers were filled using the intermediate procedure.

Acoustic data processing first entailed translating the output from the HARP acquisition software into a format required for a manual-tracking program (FET Tracker) recently developed by William T. Nagy, USACE, Fisheries Field Unit. We used the FET Tracker to display the acoustic data in echogram form and save the user-selected fish traces in output files that were later read into Statistical Analysis System (SAS) for post-processing and analysis. The user selects acceptable fish traces by framing the traces with the mouse and clicking on the 'accept' button or by painting echoes. Acceptable traces were defined as traces having greater than 3 echoes and no more than a four-ping gap (four pings without an echo). The tracker has several display schemes for color-coding by echo amplitude. This feature is especially important in noisy environments when low amplitude echoes from bubble clouds can diminish the ability to distinguish fish traces from noise. Additionally, the FET Tracker has a "barrel-view" feature that allows users to view fish traces in the x-y plane, indicating the target's direction of travel.

Table 1. Parameters and values used for hydroacoustic detectability modeling.

Parameter	Value
Nominal Beamwidth in Degrees	6
Beam Tilt in Degrees	0
Near Blanking Range (m)	1
Ping Rate in pings/sec	10
Mean Target Strength (dB)	-44.09
Target Strength Standard Dev. (dB)	2.1
Collection Threshold (dB)	-56
Minimum Echoes for Detection	4
Maximum Ping Gap Allowed	4
Number of Fish for Simulation	500000
Maximum Range (m)	12
Estimated Fish Speed (m/sec)	
Range < 1.5 m	0.14
≥ 1.5 and < 2.5 m	0.18
≥ 2.5 and < 3.5 m	0.2
≥ 3.5 and < 4.5 m	0.19
≥ 4.5 and < 5.5 m	0.22
≥ 5.5 and < 6.5 m	0.28
≥ 6.5 and < 7.5 m	0.32
≥ 7.5 and < 8.5 m	0.36
≥ 8.5 and < 9.5 m	0.35
≥ 9.5 and < 10.5 m	0.32
≥ 10.5	0.29

All tracked fish were spatially expanded based upon Equation 1 below.

$$\text{Expanded Fish} = CW / (MID\_R \times TAN(EBA/2) \times 2), \qquad (1)$$

where CW is culvert width in m, MID_R is the mid-point range of a trace in m, TAN is the tangent, and EBA is effective beam angle in degrees. Effective beam angle depends upon the detectability of fish of different sizes in the acoustic beam and is a function of nominal beam width and ping rate (pings / sec) as well as fish size, aspect, trajectory, velocity, and range.

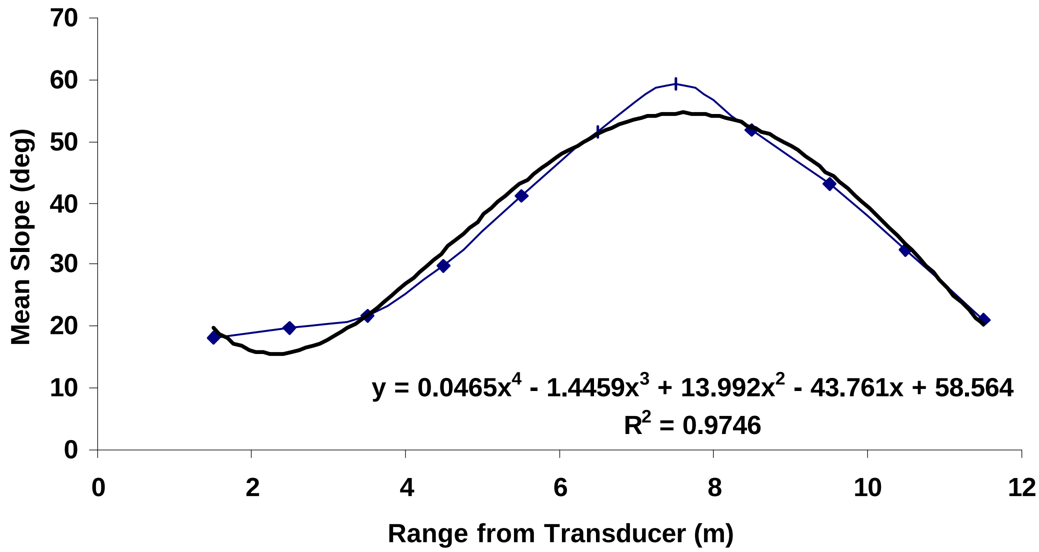

Figure 4. Relation of mean slope of fish traces with range from transducer. The 4th order polynomial equation describing the bold trendline fitted to the data was used in the detectability model.

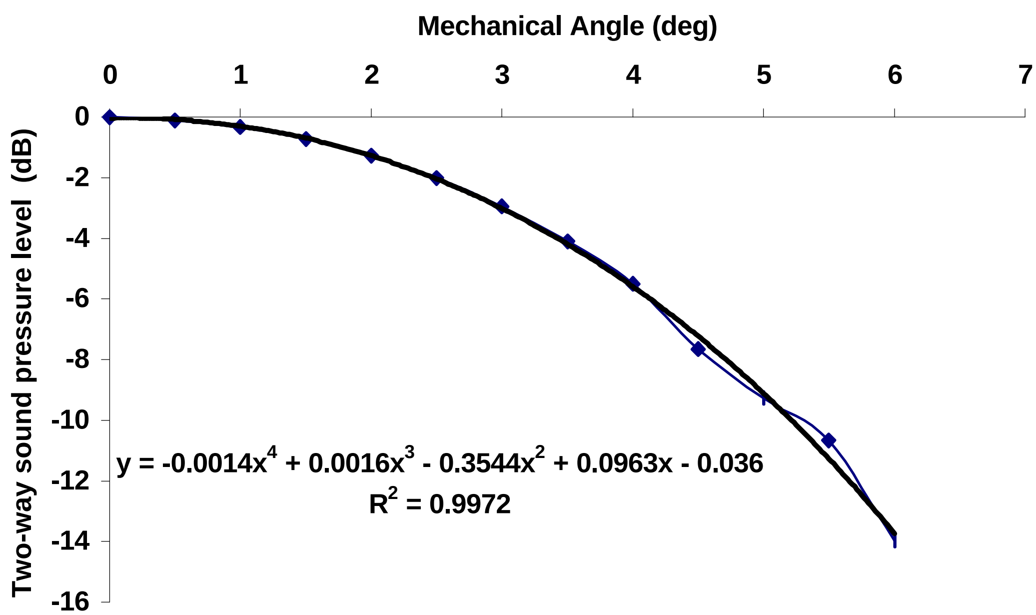

Figure 5. Relation of two-way sound pressure level as a function of mechanical angle for the transducers used to sample fish entrainment through the lock filling culverts. The 4th order polynomial equation describing the bold trendline fitted to the data was used in the detectability model.

Data reported herein over a diel cycle are standardized based on the number of minutes sampled for each hour of the day over the course of the study. The standardized counts were then expanded to the whole hour. During the period when the south wall transducer was inoperable due to a broken transducer mount (10-17 July), entrainment into the south wall culvert was estimated based on the proportion of fish detected in the south wall beam relative to the proportion detected in the north wall beam during periods when both transducers were operable. Fish were defined as entrained into the culvert based on their direction of travel (on the azimuth plane) through the beam (Figure 6) for fish distributed from 1 m above the culvert to the floor. With the exception of the target strength distribution analysis, all hydroacoustic data reported herein describe only fish with average target strengths less than –37.5 dB. According to Love's (1977) equation, a fish with average target strength of –37.5 dB sampled at dorsal aspect would equate to a length of 25.5 cm, which is approximately the size of the largest juvenile salmonid likely to be encountered at the Locks.

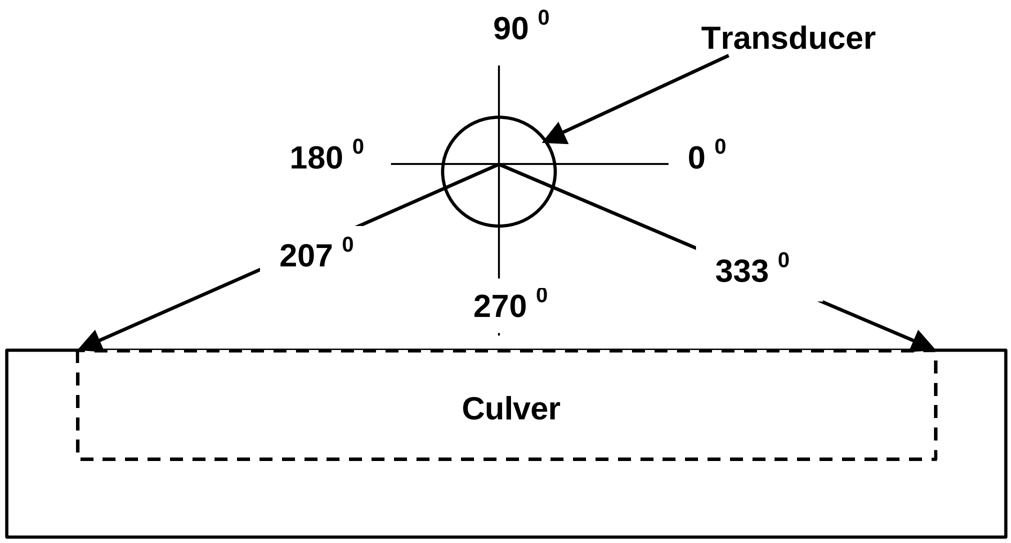

Figure 6. Conceptual diagram showing the horizontal angle of bearing (azimuth) for fish traces passing through the hydroacoustic beams. Fish traces with midranges from 1 m above the culvert entrance to the floor and with azimuth values between 207 and 333 degrees during fill events were considered entrained fish.

Table 2. List of sampled fill events during the study period at Hiram M. Chittenden Locks in 2000. Lock chambers filled were either full (F) or upper (U). Valve procedures (fill types) used were "continuous" (C), "graduated" (G), and "intermediate" (I).

Date	Start Time	End Time	Chamber	Fill Type	Date	Start Time	End Time	Chamber	Fill Type
19-May	1656	1707	F	I	26-May	1203	1214	F	I
19-May	1925	1930	U	I	26-May	1318	1328	U	I
19-May	2203	2210	U	I	26-May	1445	1456	U	I
20-May	516	522	U	I	26-May	1558	1614	F	I
20-May	905	915	U	I	26-May	1745	1801	F	I
20-May	1146	1202	U	I	26-May	2003	2014	U	I
20-May	1553	1608	F	I	27-May	900	910	U	I
21-May	736	744	F	I	27-May	1010	1020	U	I
21-May	1303	1320	U	I	27-May	1156	1205	U	I
21-May	1533	1550	F	I	27-May	1302	1311	U	I
21-May	1718	1730	F	I	28-May	608	619	U	I
21-May	2127	2132	U	I	28-May	1324	1333	U	I
22-May	134	143	F	I	28-May	1448	1457	U	I
22-May	1450	1506	U	I	28-May	1606	1616	U	I
22-May	1604	1622	F	I	28-May	1802	1816	F	I
23-May	305	314	U	I	29-May	711	723	U	I
23-May	1012	1022	U	I	29-May	956	1009	U	I
23-May	1315	1330	U	I	29-May	1145	1158	F	I
23-May	1436	1452	U	G	29-May	1401	1411	F	I
23-May	1552	1600	U	C	29-May	1536	1546	F	I
23-May	1746	1759	U	I	29-May	1726	1737	F	I
23-May	2138	2145	F	I	29-May	1832	1842	U	I
24-May	343	353	U	I	29-May	2003	2017	F	I
24-May	455	505	U	I	29-May	2059	2111	U	I
24-May	1225	1237	U	I	30-May	915	930	U	I
24-May	1416	1423	U	C	30-May	1207	1221	F	I
24-May	1521	1537	U	I	30-May	1453	1500	U	I
24-May	1618	1633	U	G	30-May	1538	1545	U	I
24-May	1859	1912	F	I	30-May	1840	1849	U	I
24-May	1957	2007	F	I	31-May	411	418	F	I
25-May	247	255	U	I	31-May	1100	1117	U	I
25-May	625	637	F	I	31-May	1319	1331	U	I
25-May	927	936	U	I	31-May	1439	1447	U	I
25-May	1055	1104	U	I	31-May	1513	1522	F	I
25-May	1244	1255	U	I	31-May	1602	1609	U	I
25-May	1521	1528	U	C	31-May	1703	1709	U	I
25-May	1610	1625	U	I	31-May	1921	1929	U	I
25-May	1836	1851	F	I	1-Jun	539	547	F	I
25-May	2047	2057	F	I	1-Jun	921	937	U	G
26-May	249	256	U	I	1-Jun	1106	1123	U	G
26-May	824	834	U	I	1-Jun	1328	1341	U	I
26-May	938	947	U	I	1-Jun	1520	1528	U	I
26-May	1118	1127	U	I	2-Jun	34	43	U	I

Table 2. (cont.).

Date	Start Time	End Time	Chamber	Fill Type	Date	Start Time	End Time	Chamber	Fill Type
2-Jun	834	847	U	I	7-Jun	1359	1413	U	G
2-Jun	941	958	U	I	7-Jun	1459	1516	U	I
2-Jun	1059	1118	U	I	7-Jun	1612	1620	U	C
2-Jun	1222	1240	U	I	7-Jun	1738	1752	U	I
2-Jun	1406	1420	U	I	7-Jun	2148	2153	U	I
2-Jun	1519	1531	F	I	8-Jun	509	522	F	I
2-Jun	1714	1720	U	I	8-Jun	1037	1045	U	I
2-Jun	1833	1838	U	I	8-Jun	1139	1148	U	I
3-Jun	7	20	F	I	8-Jun	1348	1353	U	C
3-Jun	227	236	F	I	8-Jun	1515	1529	U	G
3-Jun	913	925	U	I	8-Jun	1614	1621	U	C
3-Jun	1123	1142	U	I	8-Jun	1653	1709	U	I
3-Jun	1533	1545	U	I	8-Jun	2021	2030	U	I
3-Jun	1703	1710	U	I	8-Jun	2205	2210	U	I
3-Jun	1855	1900	U	I	8-Jun	2307	2312	F	I
3-Jun	2137	2145	F	I	9-Jun	756	807	U	I
4-Jun	837	846	U	I	9-Jun	911	921	U	I
4-Jun	1049	1104	U	I	9-Jun	957	1006	U	I
4-Jun	1252	1312	U	I	9-Jun	1043	1050	U	I
4-Jun	1413	1434	F	I	9-Jun	1216	1225	U	I
4-Jun	1602	1615	U	I	9-Jun	1607	1620	U	I
4-Jun	1719	1729	F	I	9-Jun	1744	1801	F	I
4-Jun	1916	1922	F	I	9-Jun	1941	1953	U	I
5-Jun	20	30	F	I	9-Jun	2052	2104	F	I
5-Jun	706	714	F	I	10-Jun	741	754	U	I
5-Jun	1044	1057	U	I	10-Jun	911	925	F	I
5-Jun	1349	1408	U	I	10-Jun	1042	1052	U	I
5-Jun	1448	1506	U	I	10-Jun	1940	1952	U	I
5-Jun	1554	1610	U	I	10-Jun	2022	2034	U	I
5-Jun	1758	1808	U	I	11-Jun	1357	1407	F	I
5-Jun	2020	2025	U	I	11-Jun	1624	1634	F	I
6-Jun	517	525	U	I	12-Jun	111	116	U	I
6-Jun	903	910	U	I	12-Jun	918	932	U	I
6-Jun	1059	1112	F	I	12-Jun	1000	1014	U	I
6-Jun	1248	1304	U	I	12-Jun	1057	1110	U	I
6-Jun	1539	1555	U	G	12-Jun	1229	1239	U	I
6-Jun	1645	1700	U	I	12-Jun	1337	1345	U	I
7-Jun	45	53	F	I	12-Jun	1451	1500	F	I
7-Jun	706	714	U	I	12-Jun	1753	1801	U	I
7-Jun	935	942	U	I	12-Jun	1919	1928	U	I
7-Jun	1117	1128	F	I	12-Jun	2010	2020	U	I
7-Jun	1301	1307	U	C	13-Jun	517	525	U	I

Table 2. (cont.).

Date	Start Time	End Time	Chamber	Fill Type	Date	Start Time	End Time	Chamber	Fill Type
13-Jun	821	836	U	I	19-Jun	702	709	U	I
13-Jun	945	953	U	C	19-Jun	741	748	U	I
13-Jun	1048	1102	U	G	19-Jun	953	1008	F	I
13-Jun	1524	1531	U	I	19-Jun	1113	1132	F	I
13-Jun	2007	2018	F	I	19-Jun	1256	1317	F	I
13-Jun	2120	2132	F	I	19-Jun	1353	1410	U	I
13-Jun	2256	2306	U	I	19-Jun	1458	1514	U	I
14-Jun	725	737	U	I	19-Jun	1922	1930	F	I
14-Jun	831	844	U	G	19-Jun	2019	2024	U	I
14-Jun	944	1000	U	I	19-Jun	2123	2129	U	I
14-Jun	1059	1107	U	C	20-Jun	349	400	F	I
14-Jun	1747	1752	U	I	20-Jun	830	838	U	I
14-Jun	1856	1901	U	I	20-Jun	930	940	U	I
14-Jun	2015	2022	U	I	20-Jun	1008	1019	U	I
15-Jun	344	352	F	I	20-Jun	1049	1102	U	I
15-Jun	816	829	U	I	20-Jun	1215	1231	U	I
15-Jun	920	935	U	G	20-Jun	1328	1345	U	I
15-Jun	1017	1025	U	C	20-Jun	1437	1454	U	G
15-Jun	1203	1219	U	I	20-Jun	1556	1603	U	C
15-Jun	1506	1515	U	I	20-Jun	1740	1751	U	I
15-Jun	1715	1721	U	I	20-Jun	1824	1832	U	I
15-Jun	2349	2358	U	I	20-Jun	2258	2304	U	I
16-Jun	257	304	U	I	20-Jun	2339	2345	U	I
16-Jun	816	828	U	I	21-Jun	15	22	U	I
16-Jun	936	952	U	I	21-Jun	207	218	F	I
16-Jun	1046	1104	U	I	21-Jun	632	639	U	I
16-Jun	1314	1333	F	I	21-Jun	938	947	U	I
16-Jun	1741	1748	F	I	21-Jun	1048	1101	F	I
16-Jun	1919	1925	F	I	21-Jun	1313	1321	U	C
16-Jun	2027	2033	U	I	21-Jun	1412	1429	U	I
17-Jun	934	948	U	I	21-Jun	1516	1531	U	G
17-Jun	1113	1130	U	I	21-Jun	1634	1648	U	I
17-Jun	1237	1254	U	I	21-Jun	1745	1756	U	I
17-Jun	1341	1356	U	I	22-Jun	344	354	U	I
17-Jun	1525	1538	F	I	22-Jun	1154	1205	U	I
17-Jun	1843	1848	U	I	22-Jun	1251	1306	U	I
18-Jun	106	114	U	I	22-Jun	1352	1407	U	G
18-Jun	723	730	U	I	22-Jun	1446	1453	U	C
18-Jun	1230	1250	F	I	22-Jun	1718	1735	F	I
18-Jun	1432	1450	F	I	22-Jun	1833	1844	U	I
18-Jun	1621	1631	U	I	23-Jun	611	620	U	I
19-Jun	12	20	U	I	23-Jun	1135	1146	U	I
19-Jun	623	630	U	I	23-Jun	1637	1652	U	I

Table 2. (cont.).

Date	Start Time	End Time	Chamber	Fill Type	Date	Start Time	End Time	Chamber	Fill Type
23-Jun	1851	1902	U	I	28-Jun	2106	2117	F	I
24-Jun	102	108	U	I	28-Jun	2144	2153	U	I
24-Jun	434	445	U	I	29-Jun	930	947	U	I
24-Jun	812	823	U	I	29-Jun	1229	1243	U	I
24-Jun	1046	1055	U	I	29-Jun	1347	1358	F	I
24-Jun	1234	1245	U	I	29-Jun	1435	1443	U	I
24-Jun	1409	1422	U	I	29-Jun	1725	1731	U	I
24-Jun	1942	1952	U	I	29-Jun	1830	1837	F	I
24-Jun	2115	2122	U	I	29-Jun	1941	1951	F	I
25-Jun	156	203	U	I	30-Jun	8	15	U	I
25-Jun	848	900	U	I	30-Jun	107	113	U	I
25-Jun	1007	1018	U	I	30-Jun	904	921	U	I
25-Jun	1101	1110	U	I	30-Jun	1048	1106	U	I
25-Jun	1408	1421	F	I	30-Jun	1223	1242	F	I
25-Jun	1641	1655	F	I	30-Jun	1425	1435	U	I
25-Jun	1840	1854	F	I	30-Jun	1845	1851	F	I
25-Jun	2006	2017	U	I	30-Jun	2001	2007	U	I
26-Jun	407	417	U	I	30-Jun	2142	2150	U	I
26-Jun	743	756	U	I	1-Jul	119	126	U	I
26-Jun	1127	1136	U	I	1-Jul	619	626	U	I
26-Jun	1412	1420	U	I	1-Jul	911	927	U	I
26-Jun	1506	1515	U	I	1-Jul	1037	1056	U	I
26-Jun	1546	1555	U	I	1-Jul	1257	1313	U	I
26-Jun	1700	1711	U	I	1-Jul	1446	1457	U	I
26-Jun	1814	1825	U	I	1-Jul	1627	1633	U	I
26-Jun	2035	2045	U	I	1-Jul	1932	1938	U	I
26-Jun	2217	2225	U	I	2-Jul	157	204	U	I
27-Jun	130	136	F	I	2-Jul	751	801	U	I
27-Jun	857	911	U	I	2-Jul	826	837	U	I
27-Jun	1110	1121	U	I	2-Jul	1019	1037	U	I
27-Jun	1303	1311	U	I	2-Jul	1217	1237	U	I
27-Jun	1341	1348	U	I	2-Jul	1404	1423	F	I
27-Jun	1448	1457	F	I	2-Jul	1535	1548	F	I
27-Jun	1655	1705	F	I	2-Jul	1905	1909	U	I
27-Jun	2221	2229	U	I	2-Jul	2328	2336	U	I
27-Jun	2318	2325	U	I	3-Jul	912	923	U	I
28-Jun	142	146	U	I	3-Jul	1226	1245	U	I
28-Jun	842	858	U	I	3-Jul	1554	1606	U	I
28-Jun	941	957	U	I	3-Jul	1904	1908	U	I
28-Jun	1052	1105	U	I	4-Jul	725	730	U	I
28-Jun	1156	1210	F	I	4-Jul	1242	1304	F	I
28-Jun	1427	1433	U	I	4-Jul	1433	1450	U	I
28-Jun	1800	1808	U	I	4-Jul	1601	1614	U	I

Table 2. (cont.).

Date	Start Time	End Time	Chamber	Fill Type	Date	Start Time	End Time	Chamber	Fill Type
4-Jul	1743	1750	U	I	13-Jul	1041	1057	U	I
5-Jul	843	849	U	I	13-Jul	1235	1250	F	I
5-Jul	1126	1141	F	I	13-Jul	1411	1420	U	I
5-Jul	1332	1353	F	I	13-Jul	1537	1544	U	I
5-Jul	1552	1611	F	I	13-Jul	1651	1657	U	I
5-Jul	1851	1901	F	I	13-Jul	1928	1935	F	I
5-Jul	2020	2025	U	I	14-Jul	331	337	U	I
6-Jul	618	628	F	I	14-Jul	1145	1204	F	I
6-Jul	932	938	U	I	14-Jul	1351	1402	U	I
6-Jul	1059	1107	U	I	14-Jul	1546	1555	F	I
6-Jul	1251	1308	F	I	14-Jul	1907	1914	F	I
6-Jul	1648	1703	U	I	14-Jul	2008	2014	U	I
6-Jul	1830	1840	U	I	15-Jul	1020	1037	U	I
6-Jul	2345	2351	F	I	15-Jul	1203	1222	F	I
7-Jul	1331	1343	U	I	15-Jul	1337	1350	U	I
7-Jul	1451	1505	U	I	15-Jul	1515	1527	F	I
7-Jul	1620	1635	U	I	15-Jul	2205	2212	U	I
7-Jul	1809	1824	F	I	16-Jul	803	814	U	I
7-Jul	1946	1957	F	I	16-Jul	1137	1157	F	I
7-Jul	2201	2205	U	I	16-Jul	1650	1659	F	I
7-Jul	2258	2303	F	I	16-Jul	2137	2144	F	I
7-Jul	2345	2349	U	I	17-Jul	244	252	U	I
8-Jul	205	212	U	I	17-Jul	947	1000	U	I
8-Jul	1238	1247	U	I	17-Jul	1116	1132	U	I
9-Jul	545	558	U	I	17-Jul	1237	1254	U	I
9-Jul	724	738	U	I	17-Jul	1345	1400	U	I
9-Jul	917	928	U	I	17-Jul	1958	2002	U	I
9-Jul	1553	1605	F	I	17-Jul	2317	2327	F	I
9-Jul	1904	1917	F	I	18-Jul	21	30	U	I
9-Jul	2029	2041	F	I	18-Jul	108	118	U	I
10-Jul	117	121	U	I	18-Jul	738	745	U	I
10-Jul	636	653	F	I	18-Jul	858	908	U	I
10-Jul	1802	1811	U	I	18-Jul	1104	1119	U	I
10-Jul	2202	2210	U	I	18-Jul	1144	1200	U	I
11-Jul	1054	1107	U	I	18-Jul	1308	1325	U	I
11-Jul	1141	1155	F	I	18-Jul	1453	1507	U	I
11-Jul	1306	1315	U	I	18-Jul	1545	1557	U	I
11-Jul	2056	2105	U	I	19-Jul	654	700	U	I
12-Jul	722	739	F	I	19-Jul	750	757	U	I
12-Jul	1345	1353	U	I	19-Jul	827	835	U	I
12-Jul	1842	1849	U	I	19-Jul	931	941	U	I
12-Jul	2134	2143	U	I	19-Jul	1019	1030	U	I
13-Jul	109	115	U	I	19-Jul	1253	1309	U	I

Table 2. (cont.).

Date	Start Time	End Time	Chamber	Fill Type	Date	Start Time	End Time	Chamber	Fill Type
19-Jul	1418	1434	U	I	25-Jul	1112	1123	F	I
19-Jul	1741	1750	U	I	25-Jul	1557	1608	F	I
19-Jul	1912	1918	U	I	26-Jul	453	506	U	I
20-Jul	100	109	U	I	26-Jul	555	610	U	I
20-Jul	957	1006	U	I	26-Jul	808	823	U	I
20-Jul	1135	1148	U	I	26-Jul	1306	1313	U	I
20-Jul	1307	1323	U	I	26-Jul	1437	1444	U	I
20-Jul	1524	1542	F	I	26-Jul	1601	1608	U	I
20-Jul	1704	1715	U	I	26-Jul	1816	1825	U	I
20-Jul	2100	2105	U	I	26-Jul	1924	1935	F	I
21-Jul	129	138	U	I	26-Jul	2255	2303	F	I
21-Jul	241	251	U	I	27-Jul	1302	1310	U	I
21-Jul	548	556	U	I	27-Jul	1516	1522	U	I
21-Jul	1036	1045	U	I	27-Jul	1626	1632	U	I
21-Jul	1435	1450	U	I	28-Jul	1518	1525	F	I
21-Jul	1600	1618	F	I	28-Jul	1631	1636	U	I
21-Jul	1744	1755	U	I	28-Jul	1852	1858	U	I
22-Jul	6	12	U	I	28-Jul	2046	2054	U	I
22-Jul	214	226	F	I	28-Jul	2124	2135	F	I
22-Jul	538	548	U	I	29-Jul	212	217	U	I
22-Jul	945	952	U	I	29-Jul	1153	1209	U	I
22-Jul	1039	1047	U	I	29-Jul	1355	1405	U	I
22-Jul	1116	1125	U	I	29-Jul	1640	1646	U	I
22-Jul	1206	1219	F	I	30-Jul	1058	1116	U	I
22-Jul	1419	1432	U	I	30-Jul	1301	1320	F	I
22-Jul	1546	1600	U	I	30-Jul	1540	1550	F	I
22-Jul	1953	2001	F	I	30-Jul	1745	1751	F	I
23-Jul	58	105	U	I	30-Jul	2103	2111	F	I
23-Jul	431	444	U	I	30-Jul	2339	2350	F	I
23-Jul	1108	1117	U	I	31-Jul	125	133	U	I
23-Jul	1207	1216	U	I	31-Jul	1536	1548	F	I
23-Jul	1400	1412	U	I	31-Jul	2007	2011	U	I
23-Jul	1638	1651	U	I	31-Jul	2117	2123	U	I
23-Jul	1827	1838	U	I	1-Aug	638	644	U	I
24-Jul	147	155	U	I	1-Aug	850	900	U	I
24-Jul	1021	1030	U	I	1-Aug	1222	1242	U	I
24-Jul	1219	1227	U	I	1-Aug	1343	1400	U	I
24-Jul	1344	1355	F	I	1-Aug	2315	2324	U	I
24-Jul	2036	2046	F	I	2-Aug	145	158	F	I
25-Jul	30	35	U	I	2-Aug	804	810	U	I
25-Jul	612	630	F	I	2-Aug	1427	1443	U	I
25-Jul	849	901	U	I	2-Aug	1605	1617	U	I
25-Jul	947	958	U	I	2-Aug	1707	1717	U	I

Table 2. (cont.).

Date	Start Time	End Time	Chamber	Fill Type	Date	Start Time	End Time	Chamber	Fill Type
2-Aug	2311	2321	F	I	4-Aug	2141	2144	U	I
3-Aug	407	417	U	I	4-Aug	2320	2325	U	I
3-Aug	619	625	U	I	5-Aug	1712	1726	F	I
3-Aug	857	905	F	I	5-Aug	1839	1848	U	I
3-Aug	1207	1221	U	I	6-Aug	612	625	U	I
3-Aug	1552	1608	F	I	6-Aug	1253	1301	U	I
3-Aug	1728	1739	F	I	6-Aug	1638	1652	F	I
3-Aug	1839	1847	F	I	6-Aug	2037	2044	U	I
3-Aug	2202	2206	U	I	6-Aug	2212	2218	F	I
4-Aug	115	125	U	I	6-Aug	2304	2309	U	I
4-Aug	227	239	U	I	7-Aug	113	119	U	I
4-Aug	632	641	F	I	7-Aug	541	557	F	I
4-Aug	823	829	U	I	7-Aug	844	855	U	I
4-Aug	937	945	F	I	7-Aug	1137	1146	F	I
4-Aug	1453	1511	F	I	7-Aug	1649	1659	U	I
4-Aug	1712	1726	F	I	7-Aug	1752	1802	U	I
4-Aug	1850	1858	U	I	7-Aug	1909	1920	F	I
4-Aug	1954	2000	U	I	7-Aug	2203	2209	U	I

Determination of Fill Event Start Times

We initially obtained start times of each fill event from the daily log of provided to us by the lockmasters, but it was clear from the hydroacoustic data that the start times from the lock logs did not match with the times in the data set. On several occasions, lock log start times were recorded when the miter gates were open. We could tell when gates were opened because horizontal lines appeared across the echograms when the miter gate ribs entered the ensonified sampling volume. This problem was likely the result of using different time indicators (wristwatches, wall clocks, etc.) to reference fill start times among the different shifts of lockmasters.

To obtain more accurate estimates of start times, we used USACE Seattle District water-level data collected from sensors deployed inside the upper and lower lock chambers to determine fill duration as a function of head differential for the various valve-opening procedures used. We calculated regression equations for predicting fill duration given the head differential and then recalculated the equation describing the relationship based only on data points reflecting lower head-per-given duration (Figure 7). Fill event start times were then calculated by subtracting the predicted fill duration from end times based on the miter gate “signature” observed in the echograms. The result of using this equation prevents us from underestimating fill durations and consequently removing fish that were entrained during the fill startup from the entrained fish estimates.

Video Imaging of Culvert Entrainment

During the annual pumpout of the large lock in November 1999, we installed a monochrome ultra-high resolution Sony SSC-M350 CCD chip camera on the north wall filling culvert entrance to sample fish entrainment during fill events. The camera was located 2 m up from the floor on the east side of the culvert entrance and aimed

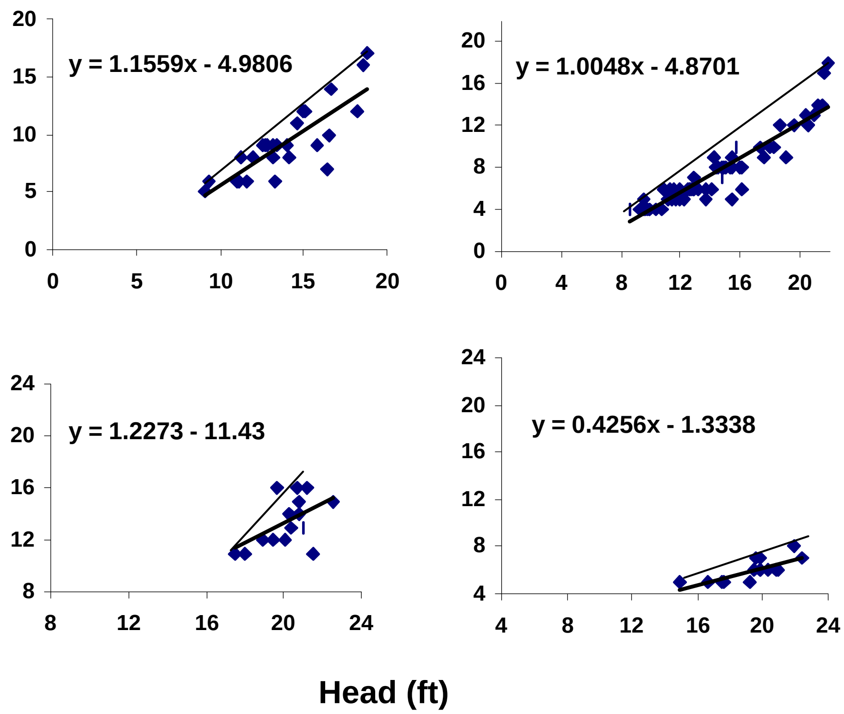

Figure 7. Scatter plots showing the relationship between head differential and fill event duration for all combinations of chamber (full and upper) and valve opening procedures used (intermediate, graduated and continuous). The bold trend lines were fitted to all plotted points. The regression equations of the lighter trend lines were used to predict fill durations for all sampled fill events to be certain that durations were not underestimated.

horizontally (westward) across the entrance and into the opening approximately 30^0. We also installed a Remote Ocean Systems 500 watt underwater droplight to provide illumination for video sampling.

Estimating smolt passage over experimental flumes

After evaluating two approaches to video record smolt passage through the flumes (see below), we determined that video sampling was not feasible and we would instead use real-time visual counts to quantify smolt passage. The visual count sampling design at the spillway flumes (Figure 8) consisted of having observers positioned on the spillway walkway deck overlooking the individual flume outfalls. Each flume was viewed for at least three 5-minute count periods per hour. After a 5-minute count period, the observer moved to a different flume to begin the next 5-minute count period. Initial flume counting position for each hourly sample was randomly chosen. The number of hours counted per day depended upon the availability of our counting staff. Whenever possible, we attempted to visually estimate flume passage for all daylight hours. Counts were generally performed between 0800 and 1700 hours. Five-minute count estimates were recorded into field notebooks and later entered into a spreadsheet. Sub-sampled counts were expanded to full hour estimates. Visual counts were obtained from 23 May to 10 July, when the last flume was shut off to conserve water. Table 3 lists the visual count sampling effort by flume and number of hours sampled per day. Additional visual counts of flume passage that were conducted the week of 15 May during periods of large lock purse seining efforts are not included in this report. Those counts, along with the counts reported herein, are analyzed and discussed relative to purse seine data collected by WDFW in Goetz et al. (in prep.).

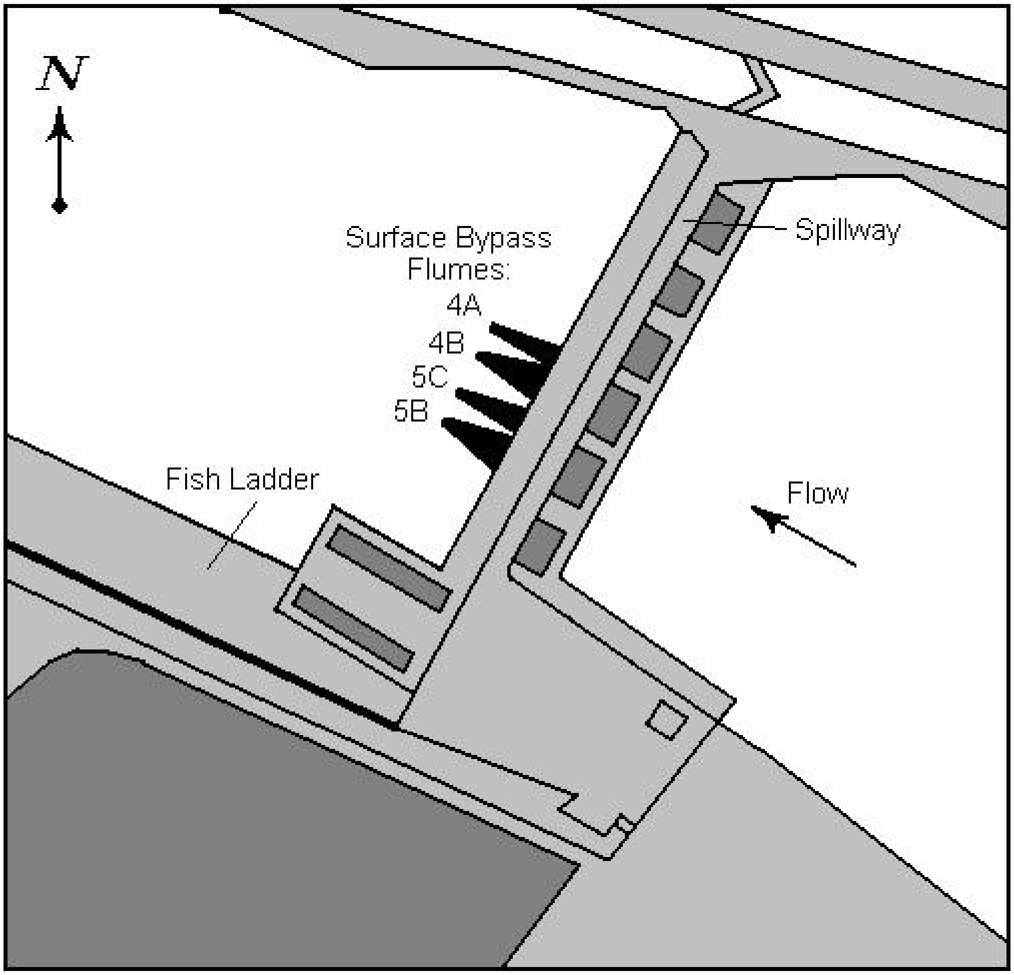

Figure 8. Plan view of spillway showing the location of the experimental flumes.

Table 3. Number of visually counted sub-sampled hours per flume per day at the Hiram M. Chittenden Locks in 2000.

Date	Flume 4A	Flume 4B	Flume 5C	Flume 5B	Date	Flume 4A	Flume 4B	Flume 5C	Flume 5B
23-May	0	6	6	6	17-Jun	0	8	8	8
24-May	0	6	6	6	18-Jun	0	0	0	0
25-May	0	8	8	8	19-Jun	0	10	10	10
26-May	0	3	3	3	20-Jun	0	10	10	10
27-May	0	8	8	8	21-Jun	0	5	5	5
28-May	0	0	0	0	22-Jun	0	10	10	10
29-May	0	0	0	0	23-Jun	0	10	10	10
30-May	0	4	4	4	24-Jun	0	0	0	0
31-May	5	6	6	6	25-Jun	0	10	10	10
1-Jun	9	9	9	9	26-Jun	0	10	10	10
2-Jun	0	0	0	0	27-Jun	0	10	10	10
3-Jun	8	8	8	8	28-Jun	0	8	8	8
4-Jun	4	4	4	4	29-Jun	0	10	10	10
5-Jun	0	0	0	0	30-Jun	0	0	2	10
6-Jun	0	7	7	7	1-Jul	0	0	0	10
7-Jun	0	5	5	5	2-Jul	0	0	5	5
8-Jun	0	10	10	10	3-Jul	0	0	0	0
9-Jun	0	9	9	9	4-Jul	0	0	0	0
10-Jun	0	10	10	10	5-Jul	0	0	10	0
11-Jun	0	10	10	10	6-Jul	0	0	10	0
12-Jun	0	8	8	8	7-Jul	0	0	8	0
13-Jun	0	11	11	11	8-Jul	0	0	10	0
14-Jun	0	10	10	10	9-Jul	0	0	10	0
15-Jun	0	11	11	11	10-Jul	0	0	2	0
16-Jun	0	10	10	10					

Velocity Measurement

As part of the continuing efforts to improve smolt passage at the Locks, we collected water velocity data in July, 2000. Data collection focused on four areas: the opening to the north filling culvert of the large lock, the upstream large lock entrance, the saltwater drain, and the entire channel upstream of the spillway from the safety cable to the end of the wing wall (Figure 9). We collected data using a boat-mounted 1200kHz acoustic Doppler current profiler (ADCP) manufactured by RD Instruments.

We mounted the ADCP just above the top center of the filling culvert and aimed it down to sample velocities that occur in the culvert openings while water is drawn through the culverts to fill the large navigation lock. The data were collected during the course of a single intermediate fill event on 18 July.

We sampled three transects across the entrance to the large lock. One transect was located approximately thirty feet upstream of the miter gates, one was 9.2 meters downstream of the entrance, and one was in the middle. We sampled three points on each transect line, one point was located at the center and the other two were halfway between the center and each side (Figure 9). Each point was sampled once during an intermediate fill event. We interpolated data between the points and between transect lines to examine overall flow patterns within the lock entrance during fill.

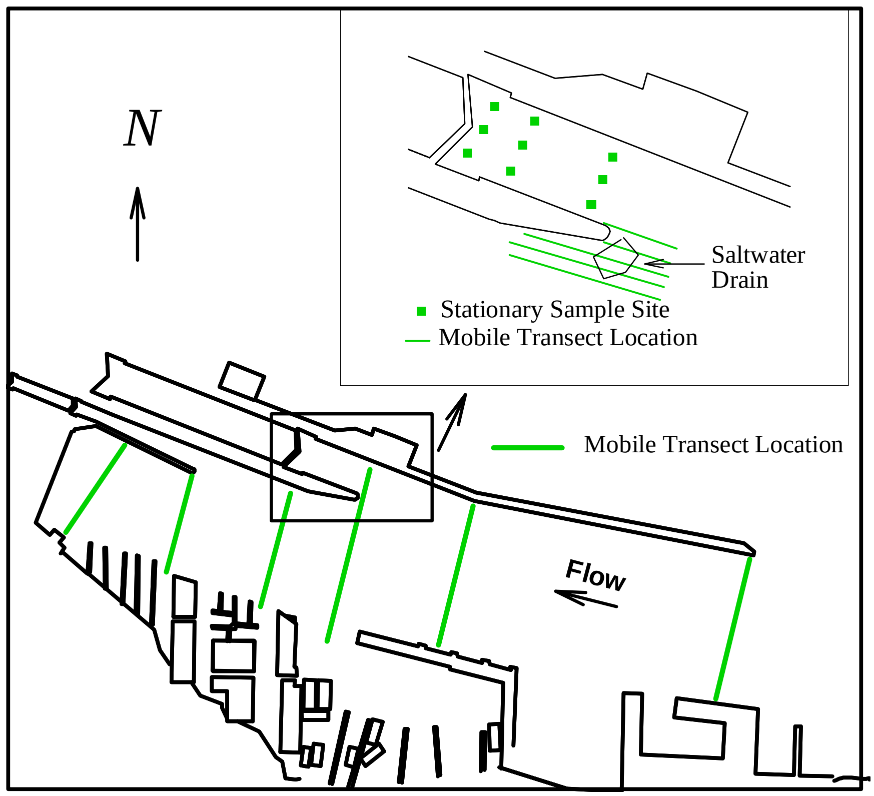

Figure 9. Sampling locations for the collection of water velocity data at the Hiram M. Chittenden Locks in July, 2000. Mobile transects are shown with lines, stationary samples are indicated by squares.

We collected data by the saltwater drain to examine any differences in flow patterns in that area that may result from changes in the volume of water discharged through the smolt flumes. We designated five 30.5 meter transects oriented upstream and located over the drain opening to sample water velocities near the saltwater drain (Figure 9). We lowered the ADCP to a depth of about 2.4 meters below the water surface and drove the boat over the transects while collecting data. All transects were sampled once while flumes 4B, 5B and 5C were open and again when only one flume (5B) was open. The saltwater drain was open half way (160 cfs) during each treatment.

We collected data with the ADCP mounted 0.5 meters below the surface along six cross-channel transects to characterize the effect of flume discharge on velocity patterns upstream of the spillway (Figure 9). We also mounted an acoustic Doppler velocimeter (ADV), manufactured by Sontek Inc., at a depth of about 2.3 meters. The ADV is a water velocity sampler that uses Doppler technology to sample a very small volume of water (about one cubic centimeter). We wanted to use the ADV to sample near the surface since the ADCP cannot sample the top 1.2 meters of the water column. The ADV, however, is of limited use in low turbidity waters. Because of the very low turbidity conditions present during data collection, data collected with the ADV was invalid.

Results

Detectability Modeling

Detectability for sampling in front of the filling culverts was uniform at the elevation of the culvert entrance (from 7.5 to 12 m; Figure 10) where the beam angles were used as factors for spatially expanding entrained fish estimates. The effective beam angle was highest one meter from the transducers and lowest at a range of two meters.

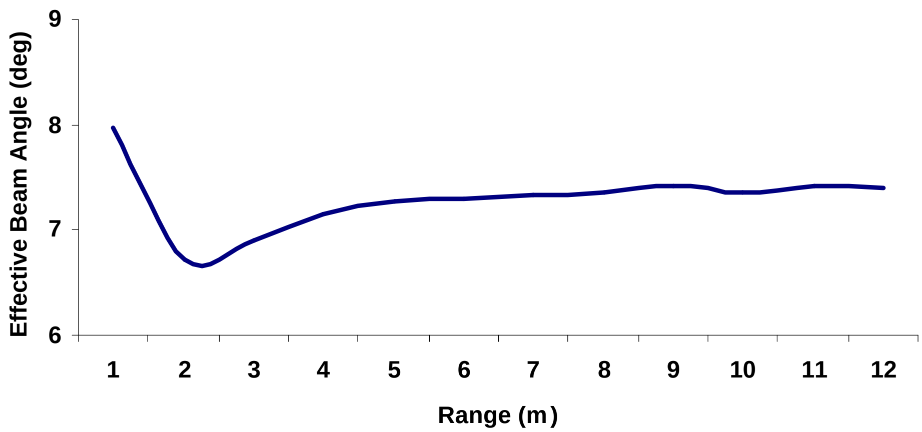

Figure 10. Effective beam angle as a function of range from the down-looking transducers deployed above the culvert entrances.

Culvert Passage

Fish passage through the filling culverts over time shows that the highest concentration of passage occurred from the latter part of June through early July and from mid July to early August (Figure 11). We estimated a total of 14,018 entrained fish through the study period of 19 May to 7 August. Total numbers and passage pattern over time (Figure 11) are based on sampling of fill events listed in Table 2 (above). This same pattern is apparent based on mean number of fish per fill per day (Figure 12), although the magnitudes of the early and mid-season modes are diminished.

Estimates of culvert entrainment during intermediate fill types were consistently higher with full chamber fills than with upper chamber fills (Figure 13). Total entrainment estimates for continuous and graduated fill types were 136 and 145 fish, respectively. Comparing fish entrainment by culvert revealed that the north culvert generally passed more fish than did the south culvert (13% more overall), especially during the latter part of the study (Figure 14). Based on t-test analysis, pooled differences were not significant (P=0.132, one-tailed test) except in July and August (P=0.039, one-tailed test).

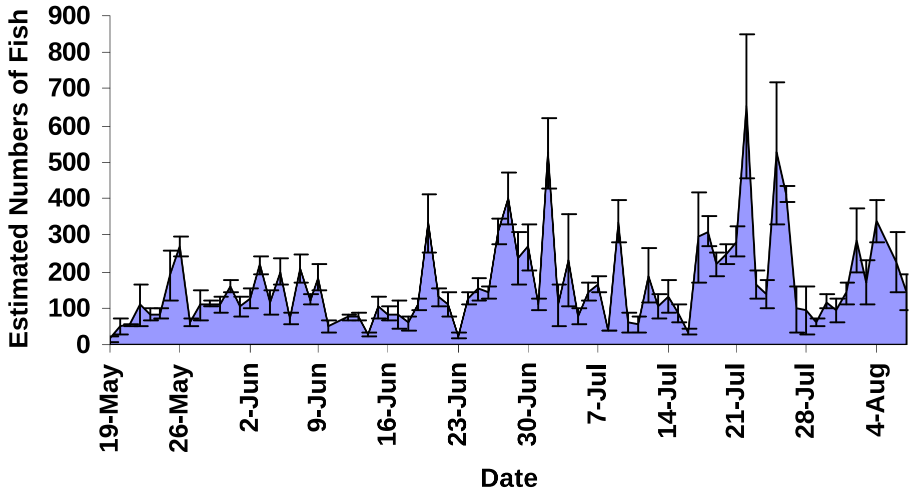

Figure 11. Culvert passage over the study period at the Hiram M. Chittenden Locks, in 2000. Estimated numbers of fish are totals by day including all sampled fill types and chambers. Error bars represent 95% confidence intervals.

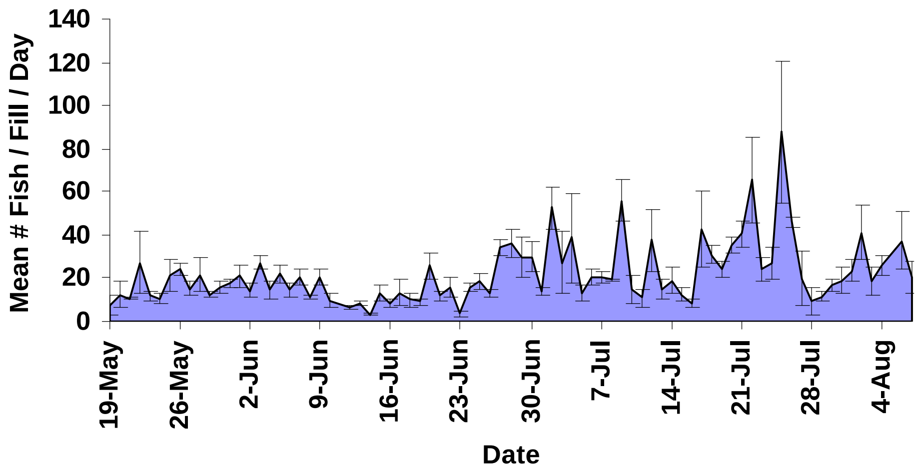

Figure 12. Mean number of entrained fish per day over the study period at the Hiram M. Chittenden Locks in 2000. Error bars represent 95% confidence intervals.

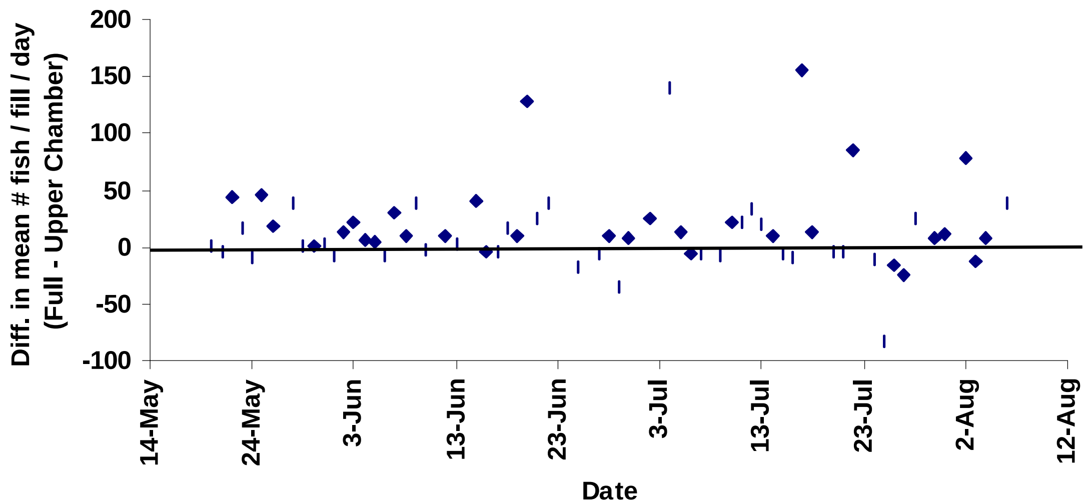

Figure 13. Difference in mean number of entrained fish per fill per day between full and upper chamber fill events.

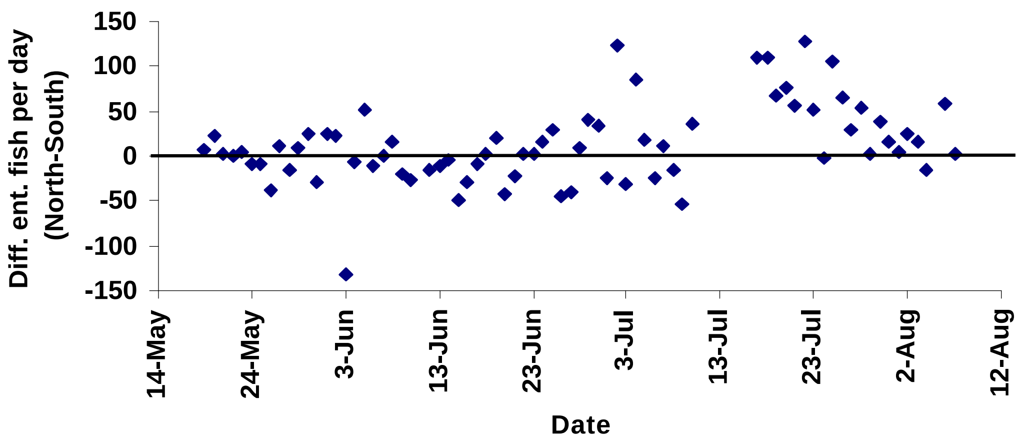

Figure 14. Difference in number of entrained fish per day between the north and south wall filling culverts.

Diel Entrainment

Hourly entrainment estimates for both upper and full chambers during intermediate fill types show that the majority of fish passage occurred during nighttime hours (Figure 15). This trend was most apparent with full chamber fill events as daylight entrainment remained relatively constant. Full chamber entrainment peaked during 0200 and 2200 hours. Upper chamber hourly entrainment was considerably more erratic, with peaks at 0100 and 0500 hours, and lowest hourly entrainment occurring at 2000 hours.

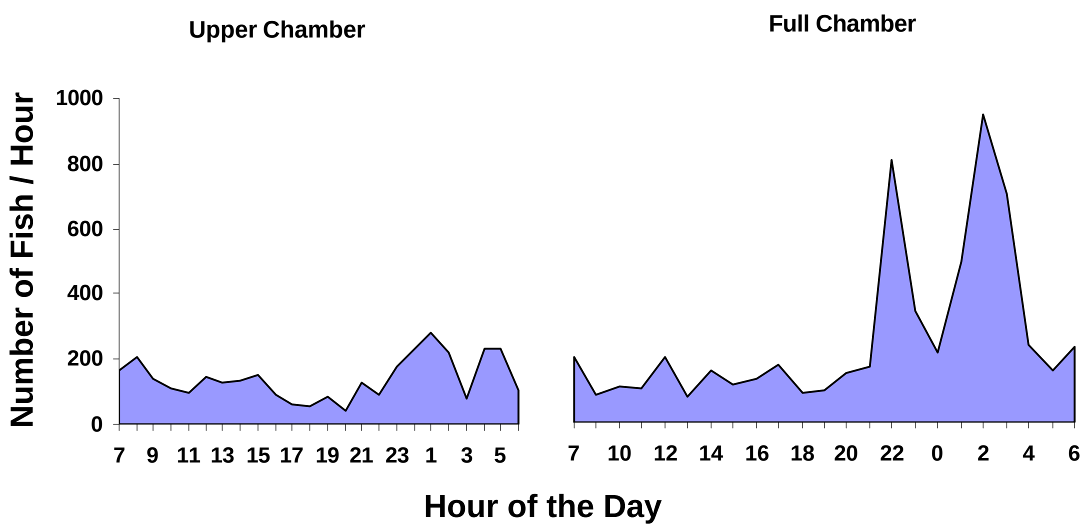

Figure 15. Hourly expanded entrainment estimates for upper and full chamber fill events.

Target Strength Distributions

Comparison of target strength distributions during all fill events among entrained and non-entrained fish clearly shows that larger targets avoided culvert passage more frequently than did smaller targets (Figure 16). The target strength distribution of entrained fish has an apparent bimodal pattern, with the two modes at –49 and –44 dB. The distribution of non-entrained fish exhibits a single mode, with the peak at –43 dB. Examination of mean target strength by time period shows that mean size of entrained fish steadily increased from the beginning of the study period until the end of the last week in June, then dropped in the second week in July before increasing again through the last portion of the study period (Figure 17). The trend over time for non-entrained fish shows a steadier pattern, with mean target strengths of about –42 dB through most of the study period. The mean target strength throughout the entire study period was –4.09 dB.

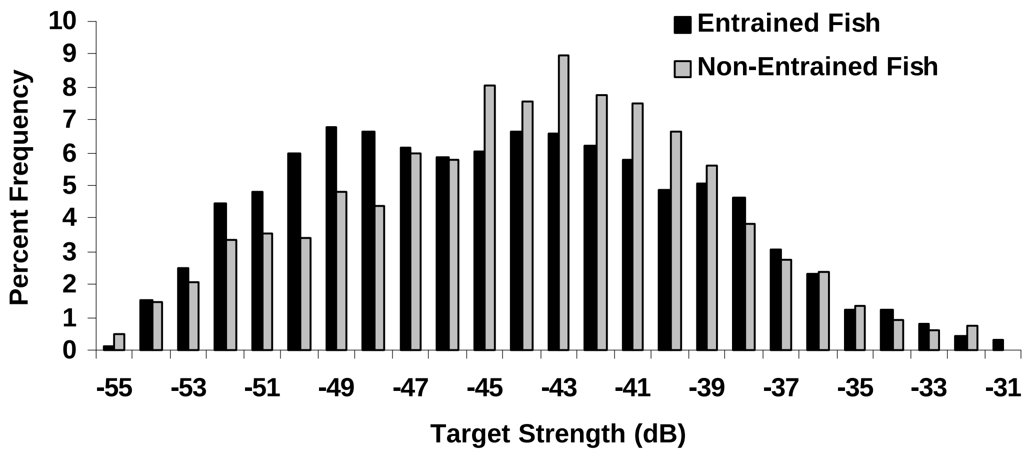

Figure 16. Target strength distributions for entrained and non-entrained fish from 19 May to 7 August, 2000.

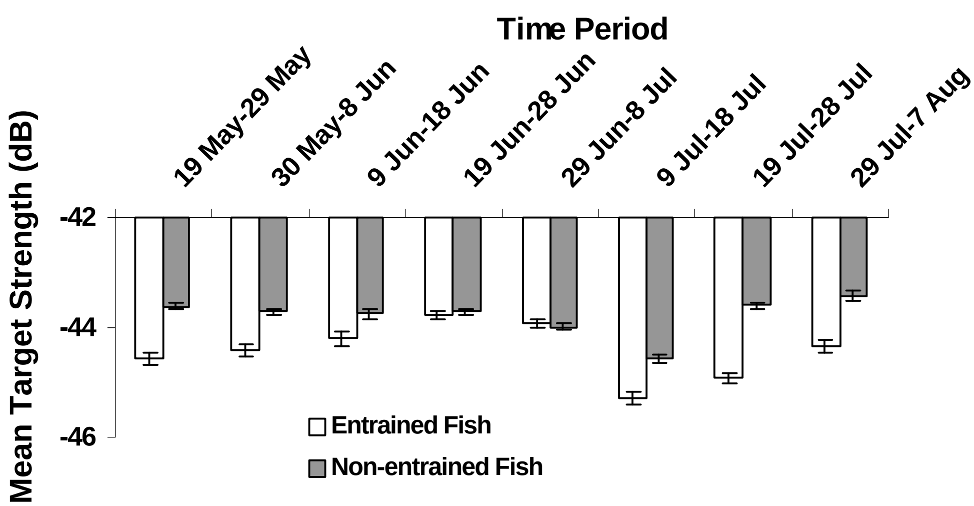

Figure 17. Mean target strengths of entrained and non-entrained fish by time period. Error bars represent standard error of the mean.

Vertical Distributions

Before and during fill events and during both daytime and nighttime periods, fish were primarily distributed within 3 m of the floor or 3 to 4 m from the water surface, with relatively few fish at mid-depths (Figure 18). Distributions were similar among the two conditions although fewer fish were near the surface and more fish were near the floor before fill events relative to fill event distributions. Entrained fish were distributed in highest proportions 2 to 3 m from the floor (Figure 19).

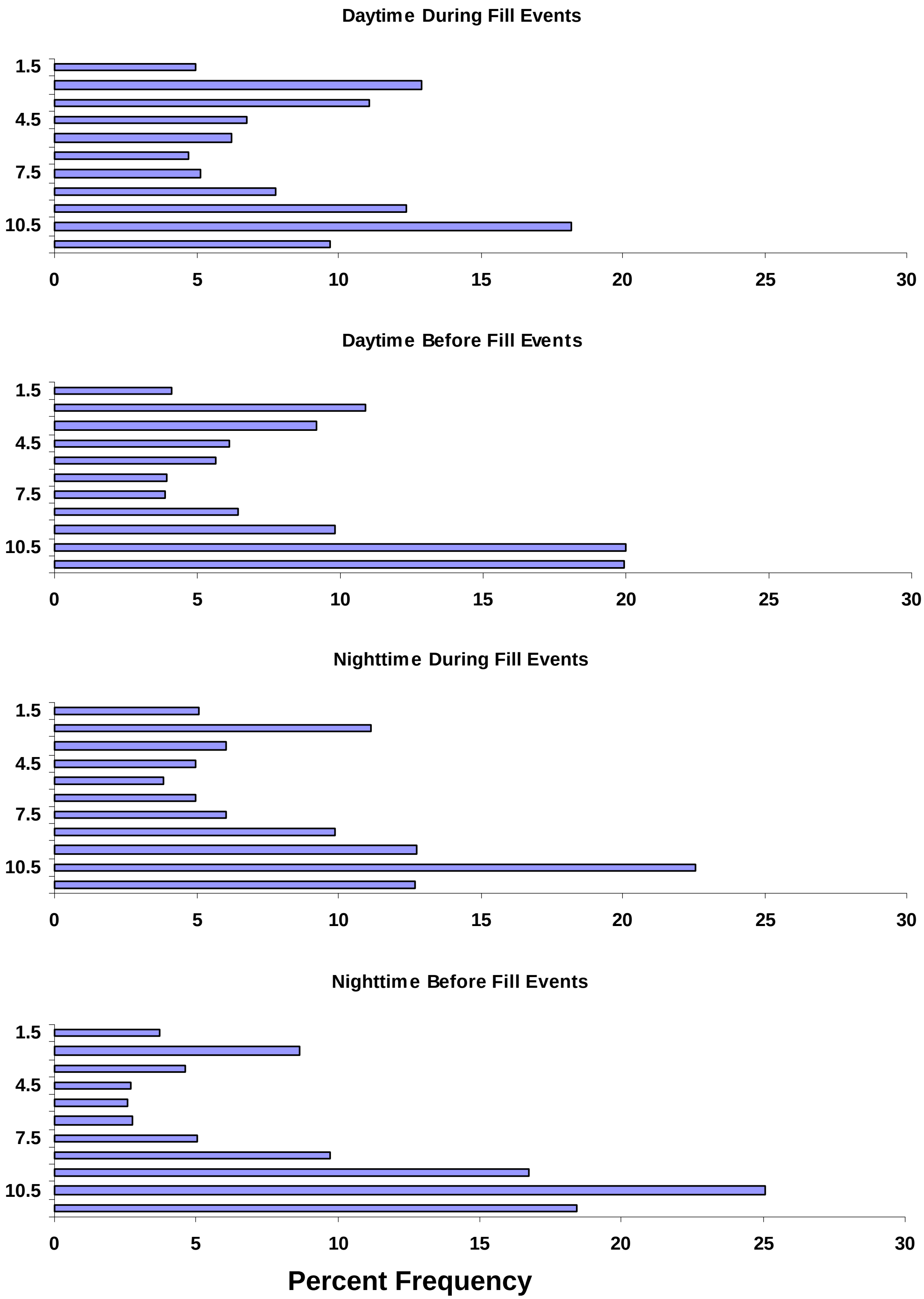

Figure 18. Vertical distributions of fish during the day and at night, before and during fill events in front of the large lock filling culverts.

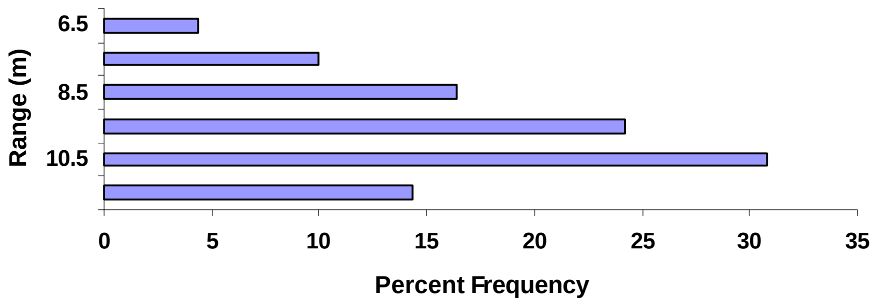

Figure 19. Frequency of vertical distribution of entrained fish.

Video Imaging of Culvert Entrainment

Attempts to capture video images of fish entrainment into the north wall filling culvert failed due to gear malfunction. Water leaked into the camera housing through the cable connection socket and soaked the camera and lens, preventing us from collecting video data. Consequently, we could not glean species composition data to supplement our hydroacoustic estimates of fish entrainment.

Flume Operations

Flumes were operated as follows during the study according to logs kept in the lock tower and notes taken during the study season:

Flume 4A: Open continuously from 15 to 21 May and from 1 to 5 June; closed 1630 on 5 June and remained closed for remainder of study.

Flume 4B: Open continuously from 15 May to 3 July except for the following temporary closures: 18 May at 1245, assumed open again at 1500; 30 May at 0900 to 31 May at 1100; 9 June from 1000 to 1430; 3 July at 1205 closed for remainder of study.

Flume 5C: Open continuously from 15 May to 29 June at 1800 except for the following temporary closures: 16 May from 0700 to 1050; 17 May from 1000 to 1100; 18 May at 1245, assumed open at 1500; 30 May from 0900 to 1230; 31 May from 0730 to 1100; 9 June from 1000 to 1430. Flume 5C was also open during the following periods: 29 June from 2400 to 30 June at 0900, 3 July at 1155 to 5 July at 1900, 6 July at 0600 to 9 July at 1900, and 10 July from 0600 to 0900.

Flume 5B: Open continuously from 15 May to 29 June at 1700 except for the following temporary closures: 16 May from 0700 to 1050 and from 1218 to 1300; 17 May from 1000 to 1100; 18 May at 1245, assumed open at 1500; 30 May from 0900 to 1230; 31 May from 0730 to 2400; 9 June from 1000 to 1430.

Flume Passage

From 23 May through 10 July, an estimated 384,060 smolts passed over the experimental spillway flumes (Figure 20). Flume passage peaked with over 43,000 fish on 25 May and averaged 1,942 fish per day prior to the shutdown of Flume 2 the afternoon of 29 June, and Flume 3 on the morning of 30 June. Flumes were shutdown due to water conservation measures associated with low Lake Washington water levels (Figure 21). After 30 June, only one flume was operable at any given time (see Table 3 above for daily sampling effort by flume). Mean hourly estimates of smolt passage over the flumes peaked in the early morning and then gradually declined before a slight increase at midday (Figure 22). Hourly passage declined again through the afternoon before peaking again at 1700 hour. We estimated a mean of 706 fish per hour through the study period.

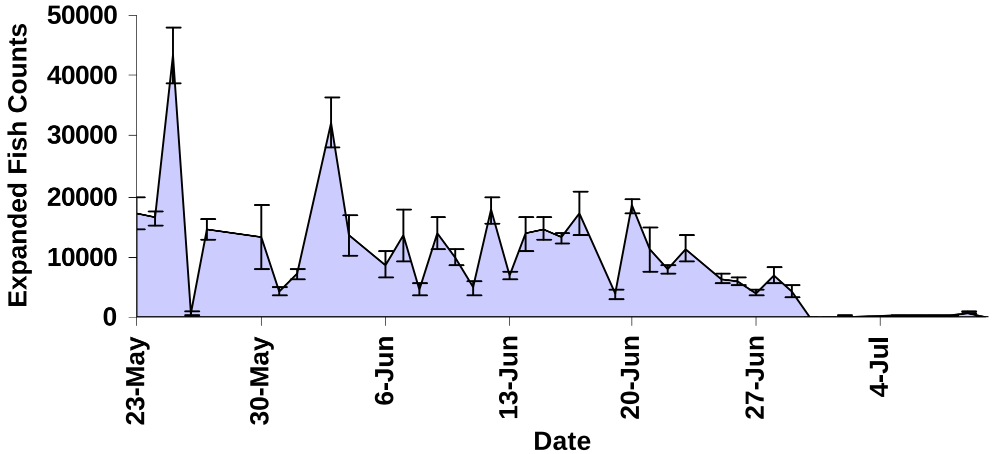

Figure 20. Estimated fish counts over the experimental spillway flumes at the Hiram M. Chittenden Locks from 23 May to 10 July, 2000. Error bars represent 95% confidence limits.

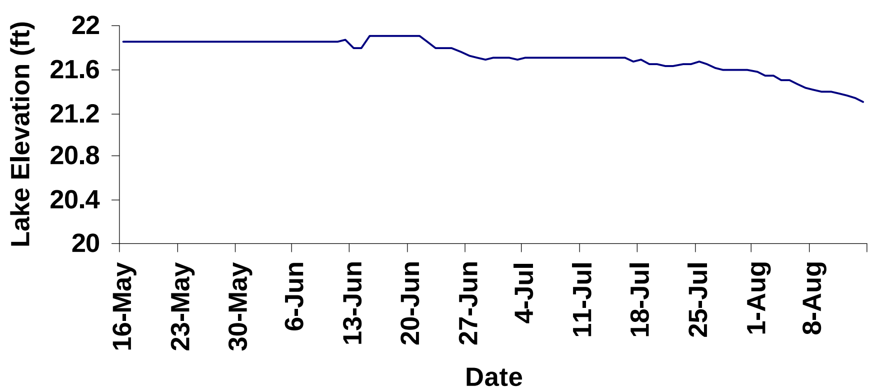

Figure 21. Lake Washington elevations through the study period. Elevation dropped to critical levels forcing the shutdown of the spillway flumes on 29 June.

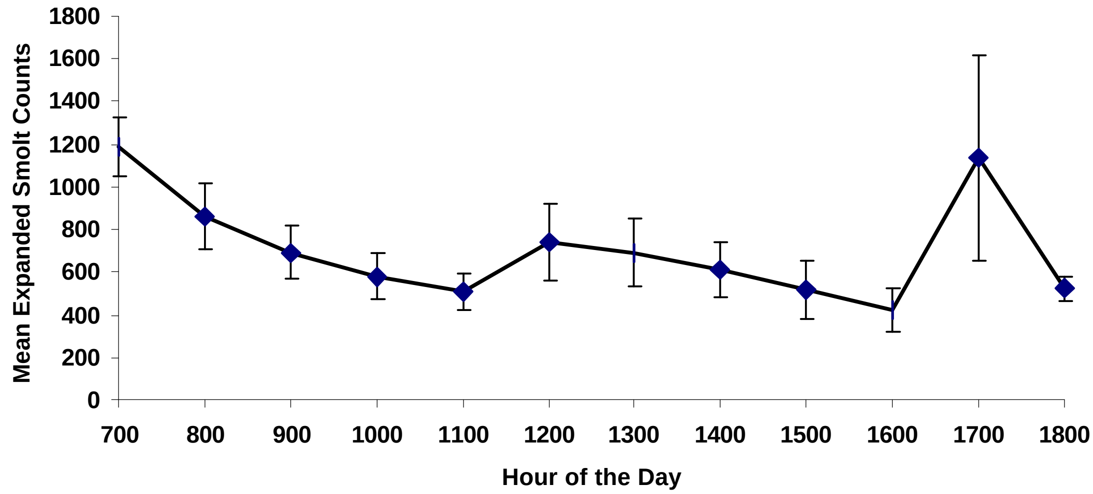

Figure 22. Mean hourly estimates of spillway flume passage during daylight hours from 23 May to 10 July, 2000. Error bars represent standard error of the mean.

Comparisons of among-flume passage estimates during days when flumes 4B, 5B, and 5C were operating showed that Flume 5B passed higher proportions of fish overall, although Flume 5C passed the most fish during the latter part of June (Figure 23). Analysis of variance showed Flume 5B to pass significantly more fish throughout the entire testing period (Table 4). This same result was true for the first and third quarters of the study period. During the second quarter, Flume 5B passed significantly greater numbers of fish than did Flume 5C, but not Flume 4B. Passage comparison during the last quarter showed Flume 4B passed significantly fewer fish than did the other two flumes. Overall, Flume 5B passed 50% of the fish, while flumes 4B and 5C passed 26 and 24%, respectively.

Unsuccessful Video Imaging Approaches

We had planned to quantify smolt passage over the spillway experimental flumes by using a video camera system to record images of passage events. The camera system consisted of four monochrome ultra-high resolution Sony SSC-M350 CCD chip cameras (one for each flume) fitted with narrow angle (25mm – 15^{o} diagonal) lenses enclosed in custom built waterproof underwater housings (Fuhrman Diversified, Inc). Smolt passage images were recorded onto T-160 VHS tapes using a Sanyo SRT-6000 real-time\time-lapse VHS video recorder set to 24-hr mode. The 24-hr mode allows for 24 hours of video to be time-lapse recorded onto a 160 minute tape (real-time recording results in 8 hours of recorded video onto a 160 minute tape; the difference is that real-time recording is approximately 30 frames per second whereas the 24-hour mode recording is approximately 10 frames per second). The four video cameras were recorded sequentially to a single tape in one-minute intervals using an Advanced Technology Video Digiswitch-8 automatic sequential switcher. The real-time video signal was displayed on a 9" Philips monochrome monitor.

On 15 May, we deployed the video cameras from steel conduit fastened along the east edge of the spillway walkway deck. The cameras were bolted to swivel-ball mounts and aimed out approximately 20^{o} upstream from vertical, centering the cameras' fields of view at mid-section of the passage flumes. Initial real-time observation of the video signal showed that the flume transition zones were extremely turbulent, making it difficult to see and effectively count passing smolts with the narrow angle lenses. On 17 May, we replaced the narrow angle lenses with 3.6mm, 105^o diagonal lenses to increase the cameras' fields-of-view beyond the transition zone. The cameras were reaimed out to approximately 30^o upstream from vertical resulting in greater fields of view encompassing almost the entire dewatering sections of the passage flumes. Upon review of 30 minutes of video tape, we determined that overhead imaging of the passage flumes remained problematic, as turbulence continued to confound our ability to effectively count passing smolts.

On 19 May, we relocated the cameras to the flume outfalls. The cameras were attached to the downstream lifting eyes of the PIT-tag readers that were mounted to the downstream ends of the flumes and aimed down and across to capture the outfall spout from the adjacent flume. For example, in Spill bay 4 the outfall from Flume 4A was sampled with the camera located on the reader attached to Flume 4B and vice versa. The outfalls from the flumes in Spill bay 5 were sampled in a similar manner.

Initial review of videotapes yielded encouraging results as the dark-colored smolts passing in the outfalls were visible against the lighter outfall spray. However, upon review of several hours of video ape over the course of two days it became apparent that this video sampling design was also problematic. Flume outfall and dewatering produced a white foamy substance that collected on the water surface at the south end of the spillway, which hindered our ability to view smolt passage over the outfalls. The brightness of the white foam overwhelmed the camera shutters and resulted in a hazy image that made it impossible to see and count passing smolts.

Relative Flume and Culvert Passage

The flumes passed a much greater proportion of fish than did the culverts (Figure 24). Flume passage comprised 98% of the number of total fish passing through these two routes throughout the comparison period, and 99% during periods when 3 or more flumes were operating. After the morning of 30 June when only a single flume was open at any given time, 46% of the fish were estimated to pass through the culvert. Prior to 30 June, culvert passage maintained a minimal contribution to estimated project passage, with the exception of 26 May when 35% passed relative to the flume estimates.

Flow Velocity Characterization at the Culvert Opening

We found temporal variations in water velocities during fill just outside of the north culvert opening (Figure 25). The duration of the intermediate fill event that we sampled was just over 600 seconds. The average sampled water velocity for the first 400 seconds of the fill was just over 0.3 m/sec. This roughly corresponds to the time before the fill valve was completely opened. After the valve was completely opened the average water velocity increased until it reached a maximum of just over 0.9 m/sec. After reaching this peak, water velocity quickly declined.

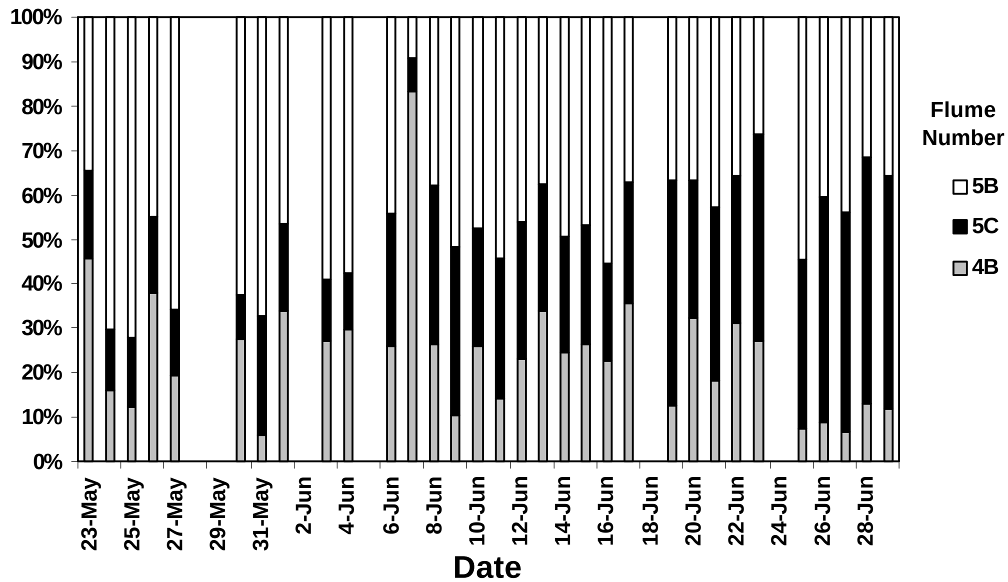

Figure 23. Proportional flume passage for all days when flumes 4B, 5B, and 5C were operational.

Table 4. Results from analysis of variance testing for differences in estimated passage among the three flumes. Means with the same letter in the grouping column are not significantly different.

Period Tested	Grouping	Mean	N	Flume	Pr > F
All Season	A	36.211	188	5B	<.0001
	B	18.212	188	5C	
	B	17.539	188	4B	
23 May-31 May	A	82.06	31	5B	<.0001
	B	25.1	31	4B	
	B	20.28	31	5C	
1 Jun-9 Jun	A	33.891	45	5B	0.0183
	AB	20.504	45	4B	
	B	14.03	45	5C	
10 Jun-18 Jun	A	31.313	49	5B	0.002
	B	18.012	49	5C	
	B	16.672	49	4B	
19 Jun-28 Jun	A	20.339	63	5C	0.0356
	A	19.119	63	5B	
	B	12.376	63	4B	

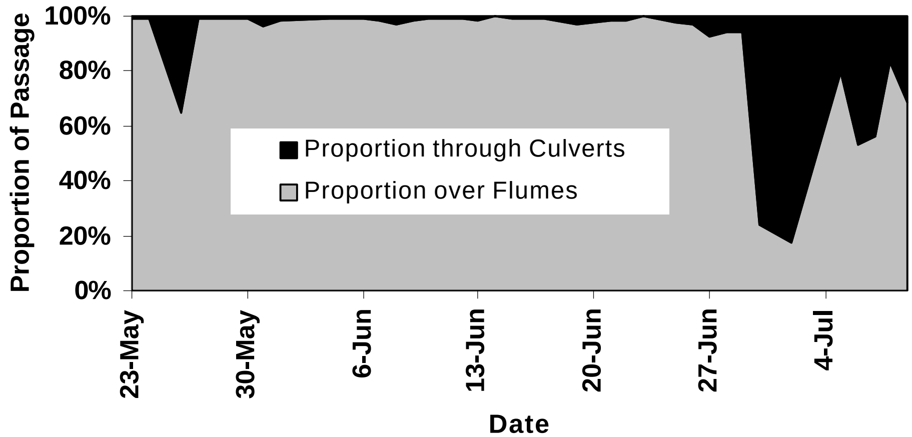

Figure 24. Relative daily proportions of flume and culvert passage estimates.

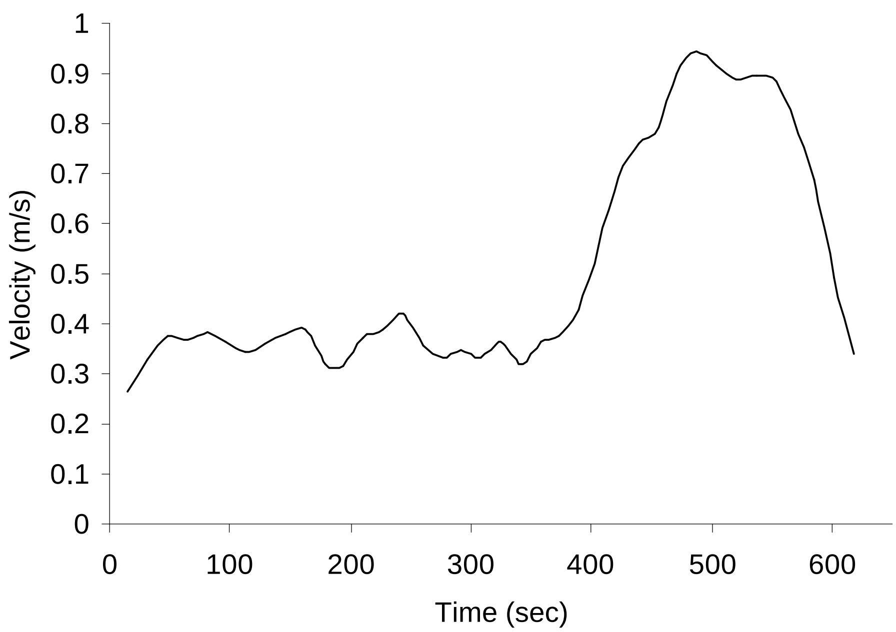

Figure 25. Temporal variation of average water velocity in front of the north filling culvert of the large lock during an intermediate fill event.

Water velocity varied little with depth from the top of the culvert to the floor of the lock opening (Figure 26). We examined the average water velocity in 0.9 meter vertical increments across the culvert opening and found very similar patterns throughout the course of the fill event.

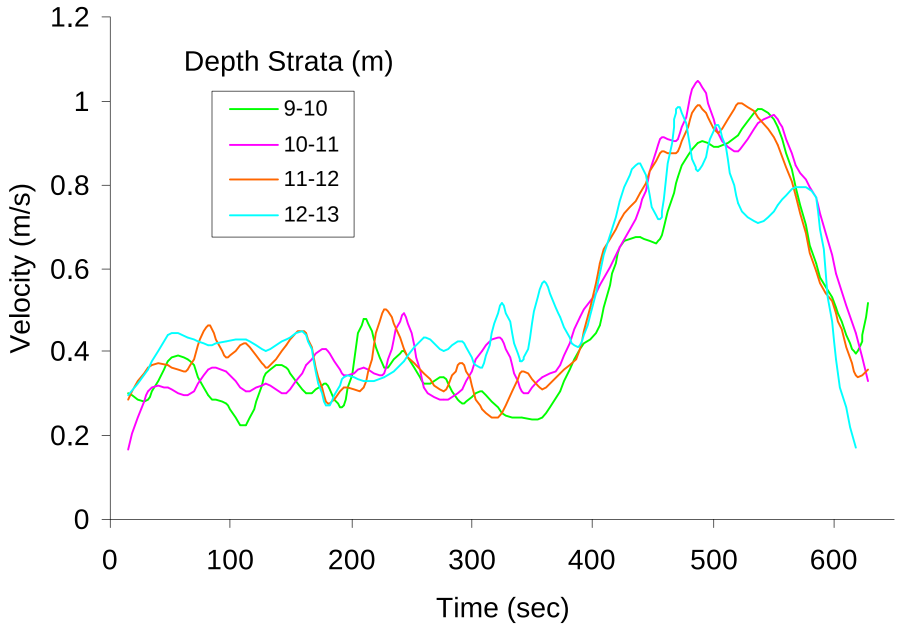

Figure 26. Temporal variation of average water velocity by depth strata in front of the north filling culvert of the large lock during an intermediate fill event.

Large Lock Entrance

Water velocities followed a similar pattern for most of the fill events sampled in the large lock entrance, particularly for samples from the east transect (Figure 27) and the west transect (Figure 28). Water velocities were about 0.15 m/sec for approximately the first two-thirds of the fill. This roughly corresponds to the time when the fill valve was partially open. The last one-third of the fill event corresponds to the time when the valve was fully open and velocities rose during this time to a high of about 0.46 m/sec and then decreased as the fill event concluded. The most noticeable difference between the velocity patterns from the east and west transects was the vertical location of the higher velocities. Higher velocities at the west transect are mostly concentrated in the lower half of the water column, near the culvert openings. At the east end of the lock entrance the higher water velocities were either equally distributed throughout the water column or were located near the surface.

The water velocity patterns from the samples taken at the center transect (Figure 29) were quite different from those at either end (Figures 27 and 28). The velocity pattern from each individual sample from the center transect, in fact, was unlike any other pattern sampled in the large lock entrance. The first sample from the center transect was taken at the north point starting at 0908 hrs and lasted about six minutes. High velocities occurred within one minute and lasted through most of the fill event, tapering off at the end. The second sample was from the center point starting at 0959 hrs and lasted about 18 minutes. Velocities were relatively low throughout the fill event. The third sample was from the south point starting at 1036 hrs and lasted 9 minutes. Velocities were moderate throughout the fill.

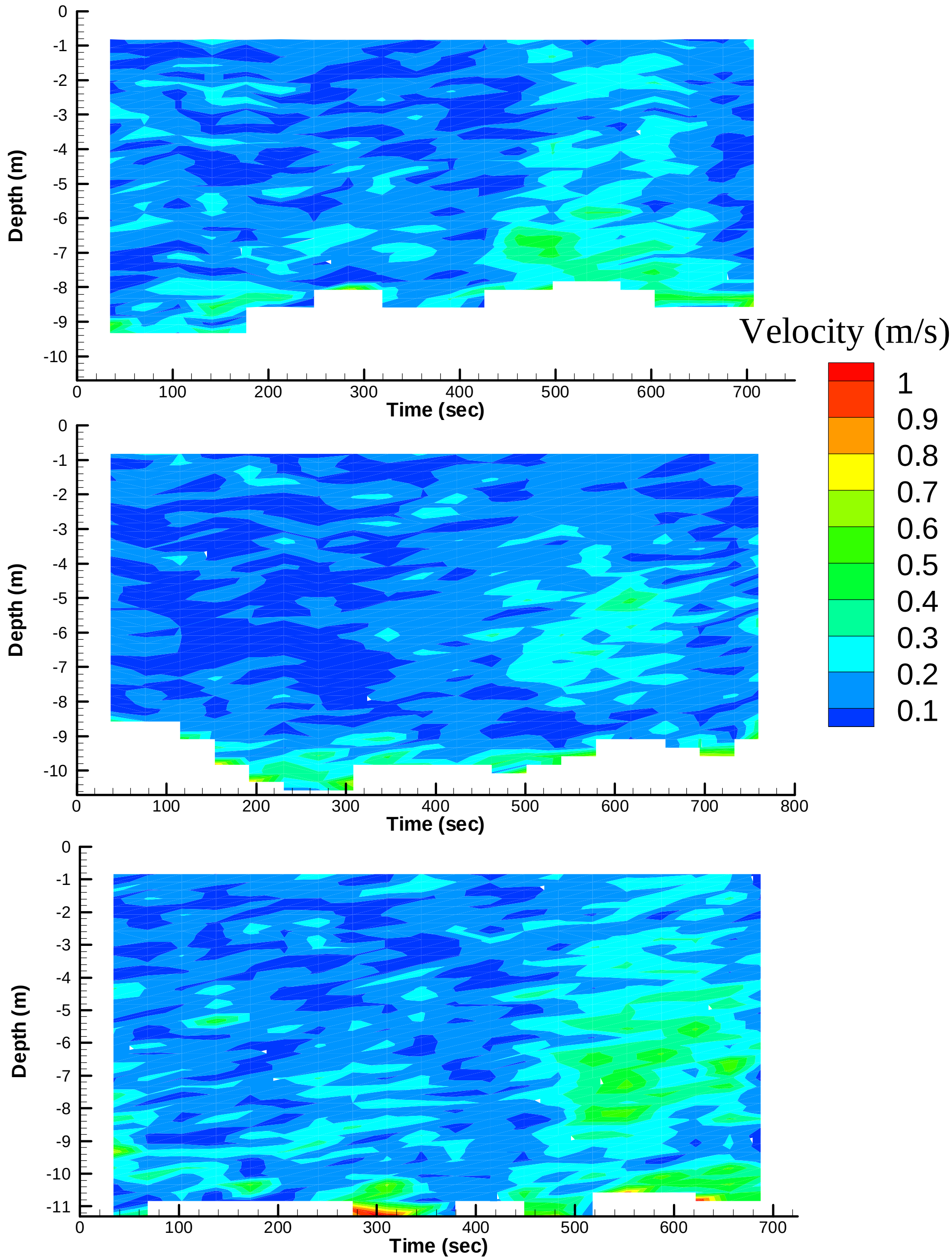

Figure 27. Temporal variation in water velocity at the south (top), middle (center), and north (bottom) sample points along the west transect inside the large lock entrance.

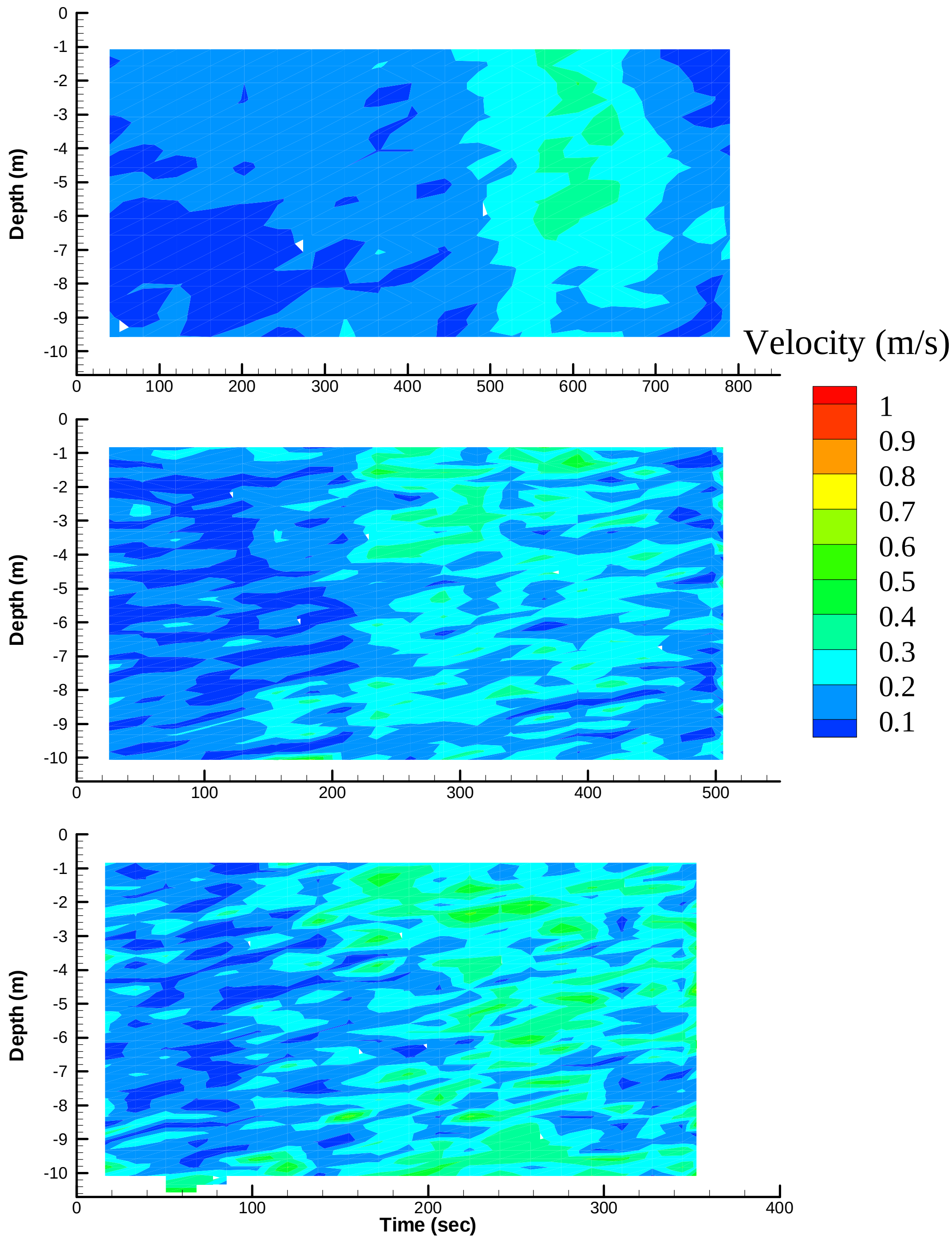

Figure 28. Temporal variation in water velocity at the south (top), middle (center) and north (bottom) sample points along the east transect inside the large lock entrance.

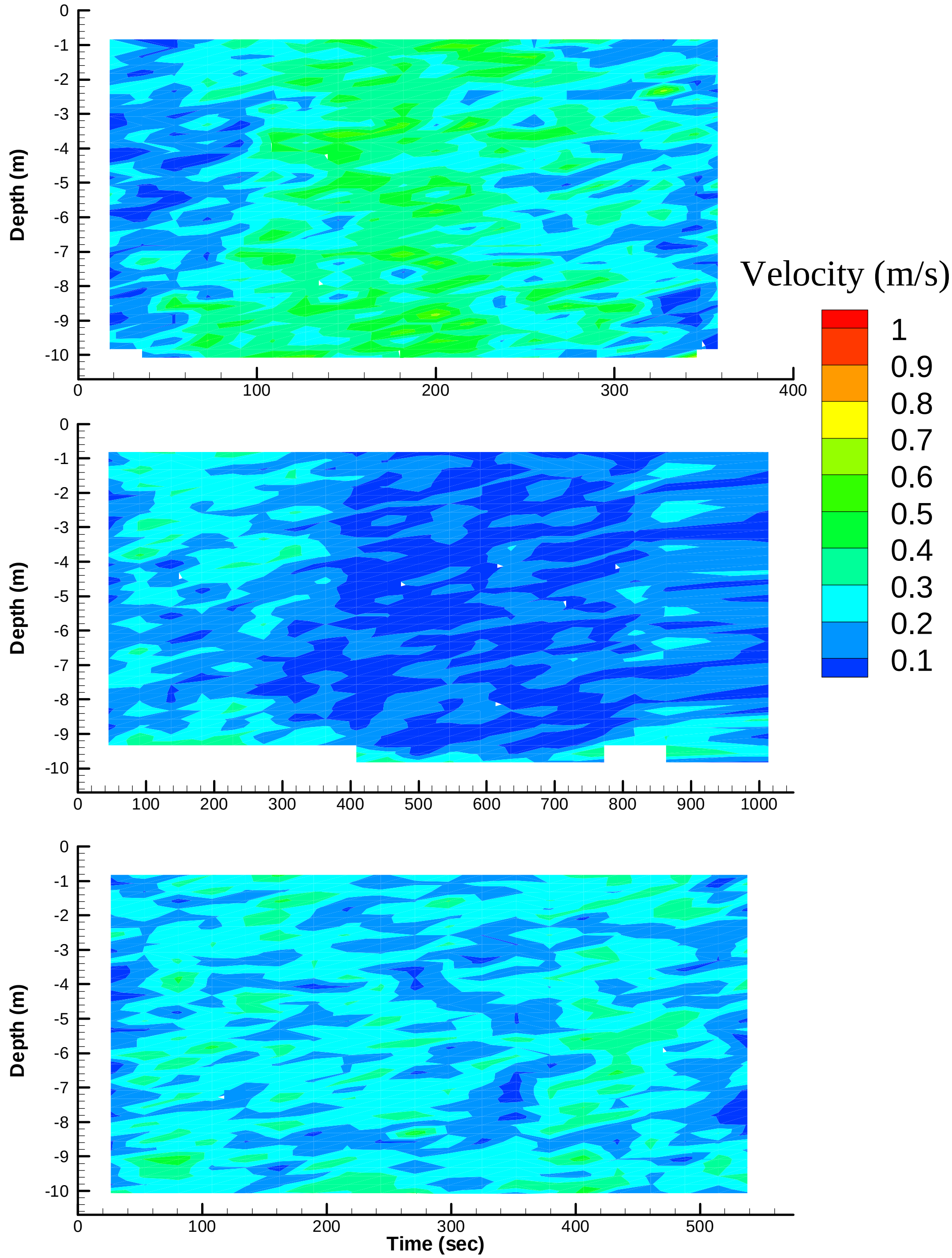

Figure 29. Temporal variation in water velocity at the south (top), middle (center), and north (bottom) sample points along the center transect inside the large lock entrance.

Saltwater Drain

Water velocities (total) in the vicinity of the saltwater drain were higher than velocities seen in the large lock opening, and they tended to be higher towards the bottom (Figures 30, 31, 32, and 33). The increase in velocity with increasing depth was not uniform, however. We detected many cells with high water velocity towards the top of the portion of the water column that we sampled (we sampled from about 3 meters below the surface to the bottom). The water velocity patterns at the saltwater drain during the two different flume discharge levels were similar. At most depth ranges, almost all velocities were below 0.6 m/sec, and the majority of these depth cells had velocities of less than 0.3 m/sec. At the bottom of the water column velocities were highest, approaching 0.8 m/sec, and there were slightly more high velocity depth cells during the high flume discharge regime.

Water velocities regarding only the vertical components were low and their directions were mixed throughout the sampled water column (Figures 34, 35, 36, and 37). Positive and negative vertical velocity values were interspersed throughout, but their values were very low compared to total water velocity. Because of the low vertical water velocities, it appears that most of the flow in this area was in the horizontal plane.

Spillway

Operation of the smolt flumes had some effect on the overall flow pattern upstream of the spillway (Figure 38). When all flumes were open, velocities were highest at the transects closest to the cable barrier. The high velocities extended east to the upstream end of the small lock pier nose, but did not reach the large lock entrance area. By contrast, flume discharge did not influence water velocities in our samples while only flume 5B was open.

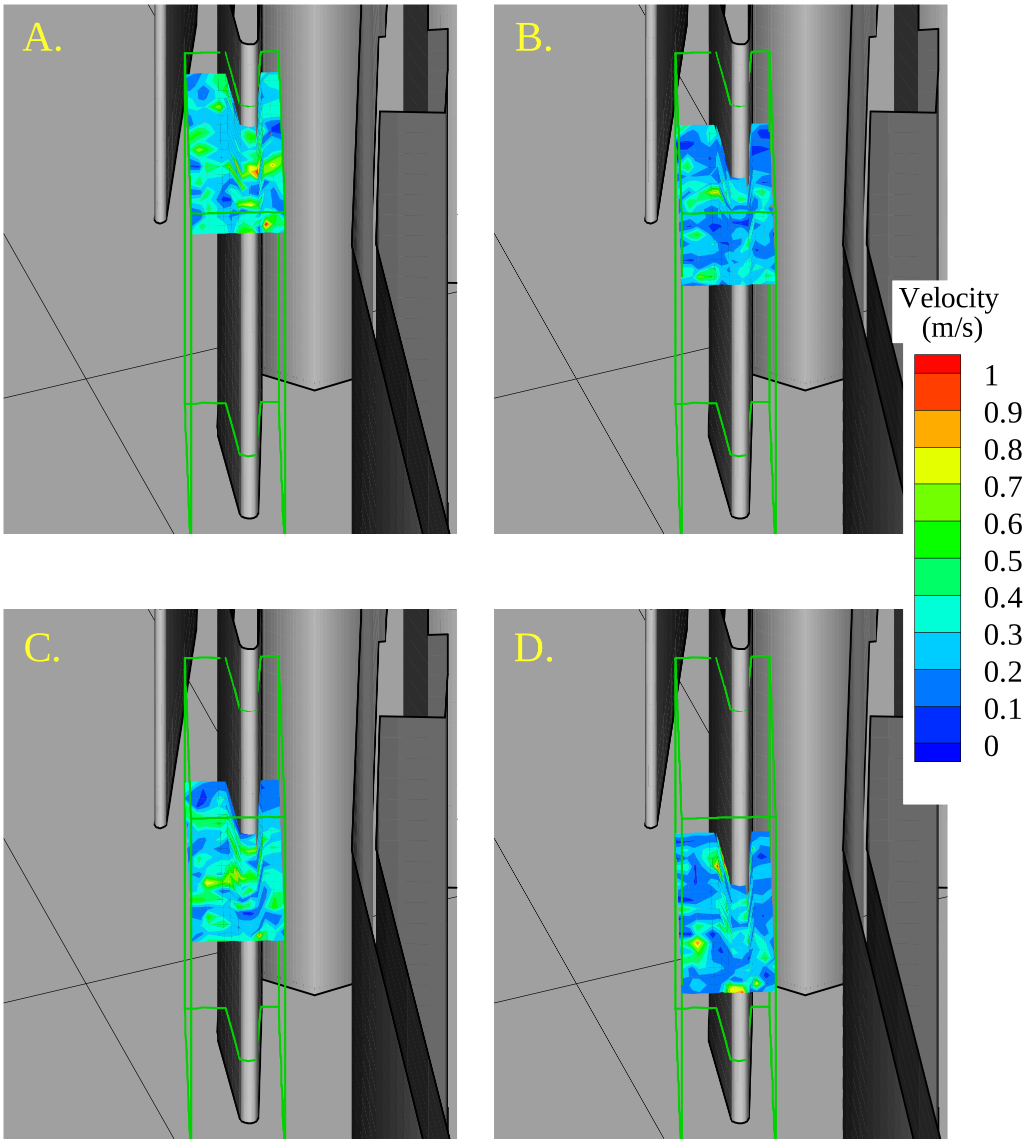

Figure 30. Contours of interpolated total water velocity by depth in the area of the saltwater drain. Depths displayed are 3 m (A), 4.6 m (B), 6.1 m (C) and 7.6 m (D). These data reflect conditions whereby flumes 4B, 5B and 5C were operational.

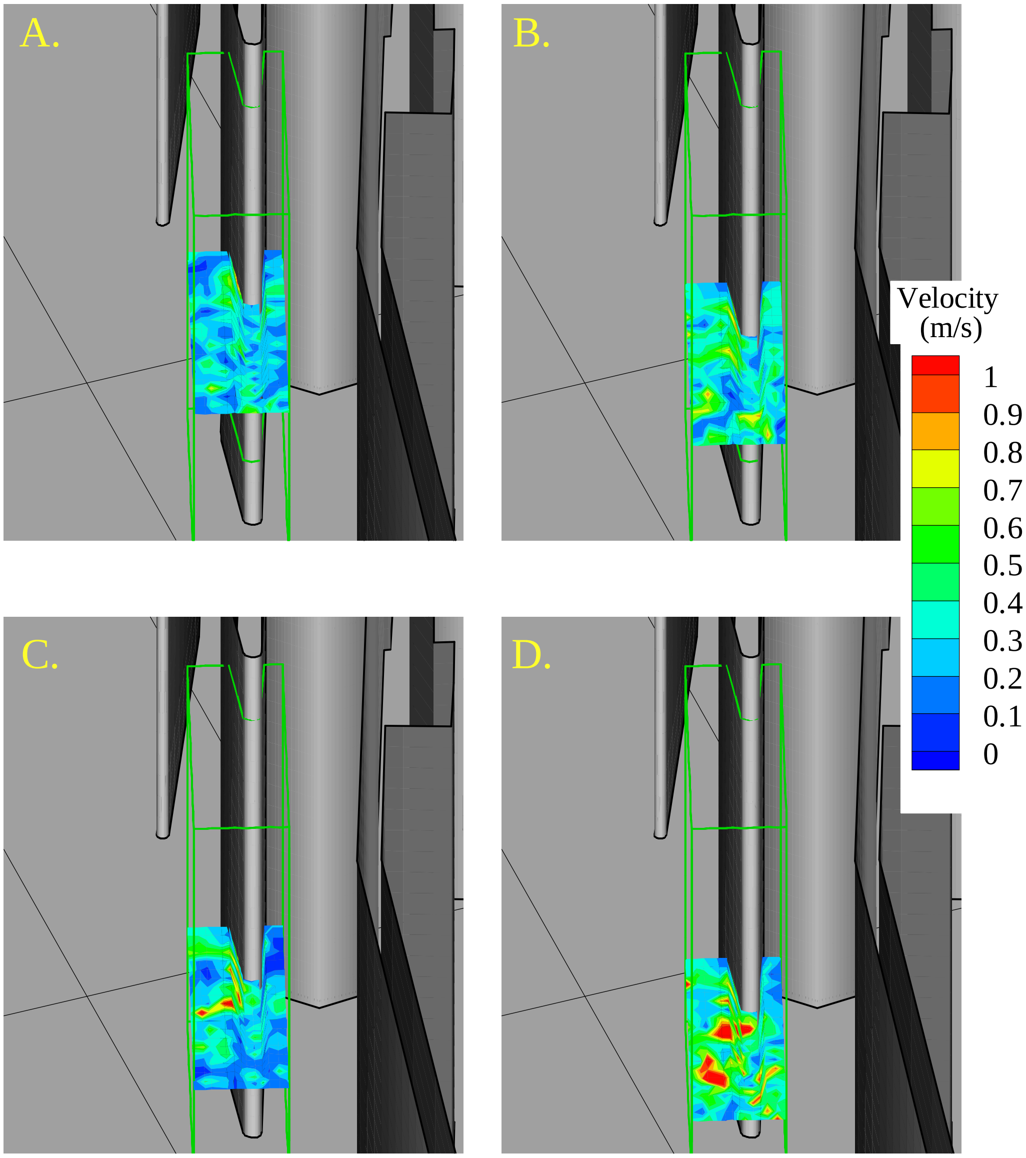

Figure 31. Contours of interpolated total water velocity by depth in the area of the saltwater drain. Depths displayed are 8.2 m (A), 9.1 m (B), 10.1 m (C) and 11 m (D). Data reflect conditions whereby flumes 4B, 5B, and 5C were operational.

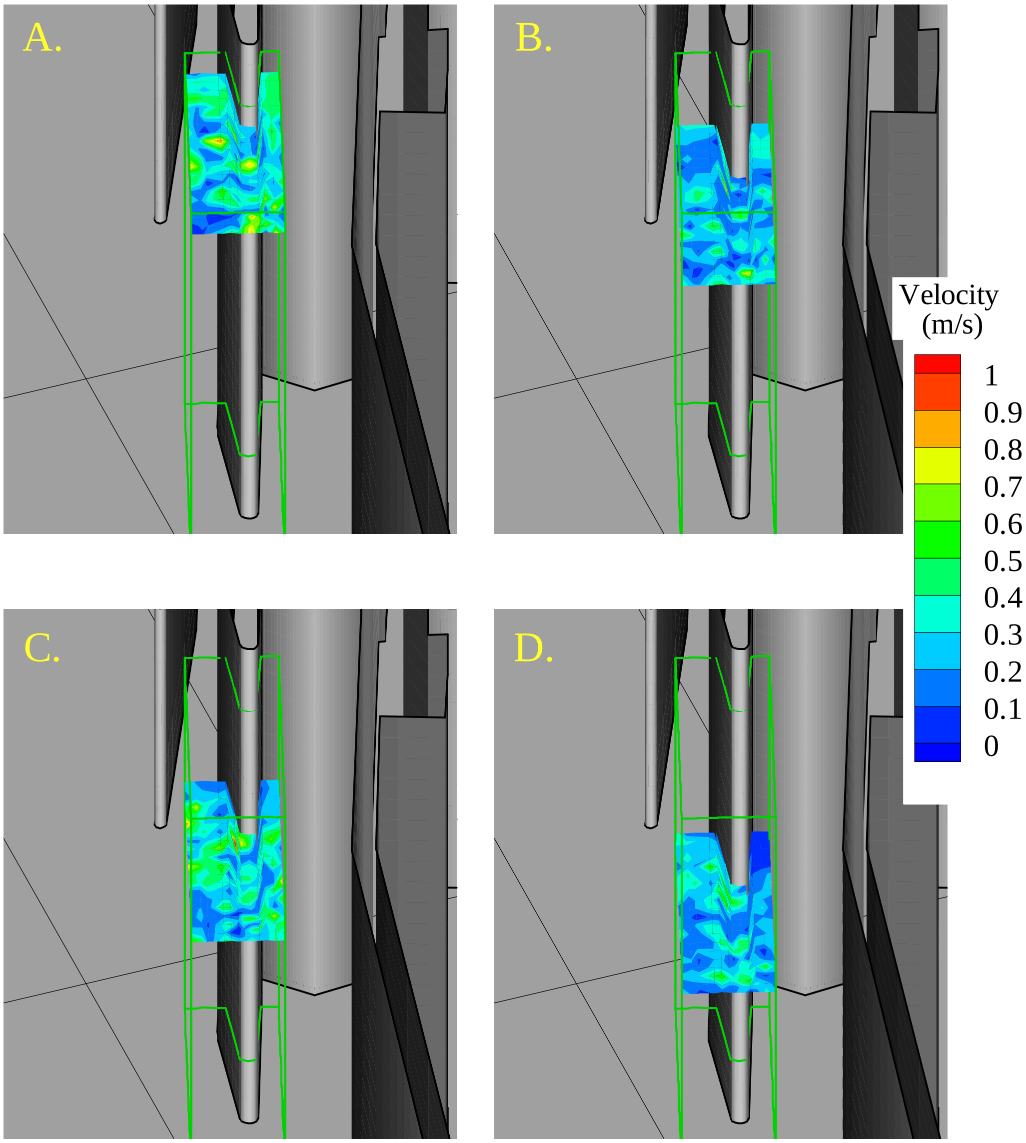

Figure 32. Contours of interpolated total water velocity by depth in the area of the saltwater drain. Depths displayed are 3 m (A), 4.6 m (B), 6.1 m (C) and 7.6 m (D). Data reflect conditions whereby only Flume 5B was operational.

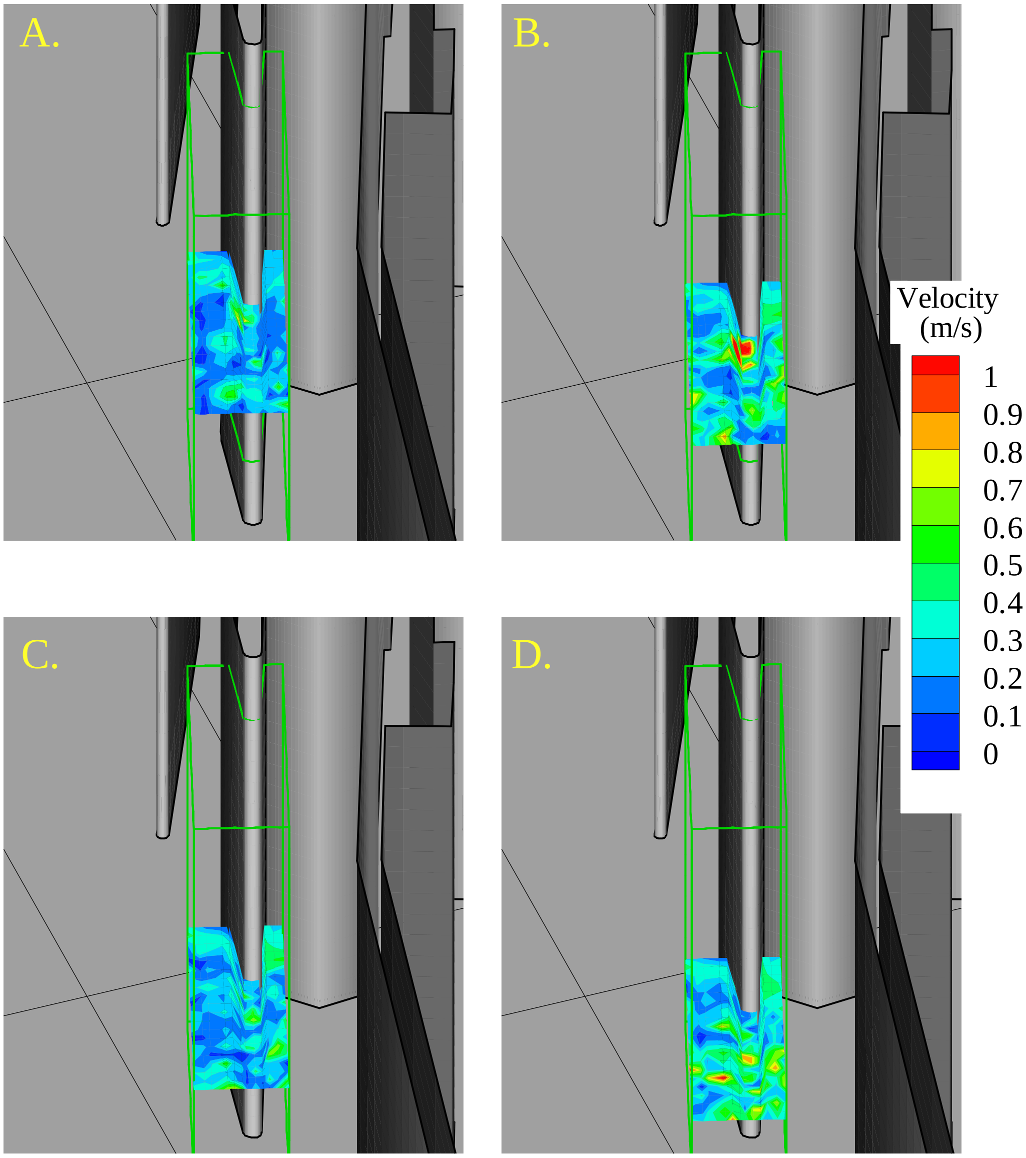

Figure 33. Contours of interpolated total water velocity by depth in the area of the saltwater drain. Depths displayed are 8.2 m (A), 9.1 m (B), 10.1 m (C) and 11 m (D). Data reflect conditions whereby only Flume 5B was operational.

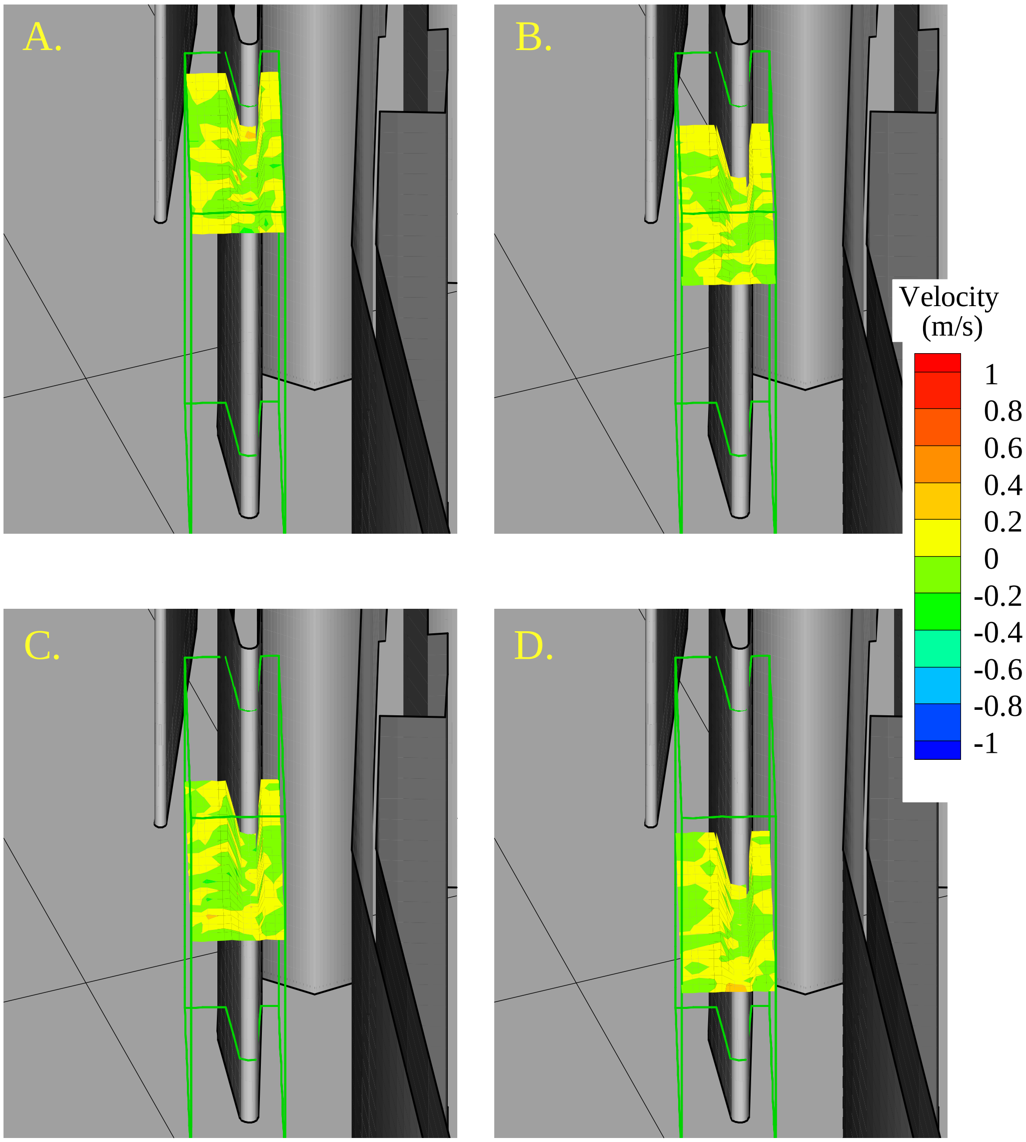

Figure 34. Contours of interpolated vertical water velocity by depth in the area of the saltwater drain. Depths displayed are 3 m (A), 4.6 m (B), 6.1 m (C) and 7.6 m (D). Data reflect conditions whereby flumes 4B, 5B, and 5C were operational.

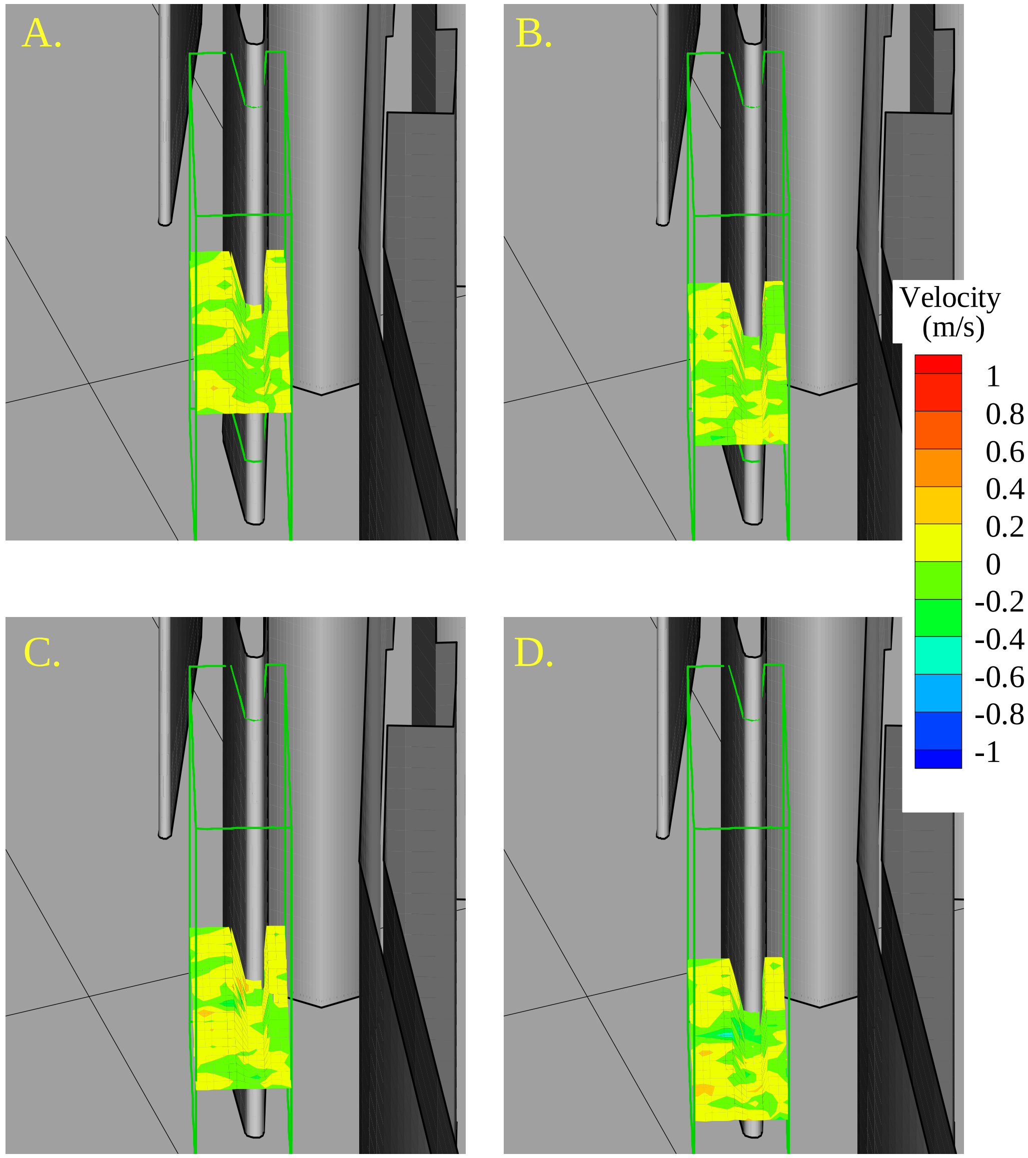

Figure 35. Contours of interpolated vertical water velocity by depth in the area of the saltwater drain. Depths displayed are: 8.2 m (A), 9.1 m (B), 10.1 m (C) and 11 m (D). Data reflect conditions whereby flumes 4B, 5B, and 5C were operational.

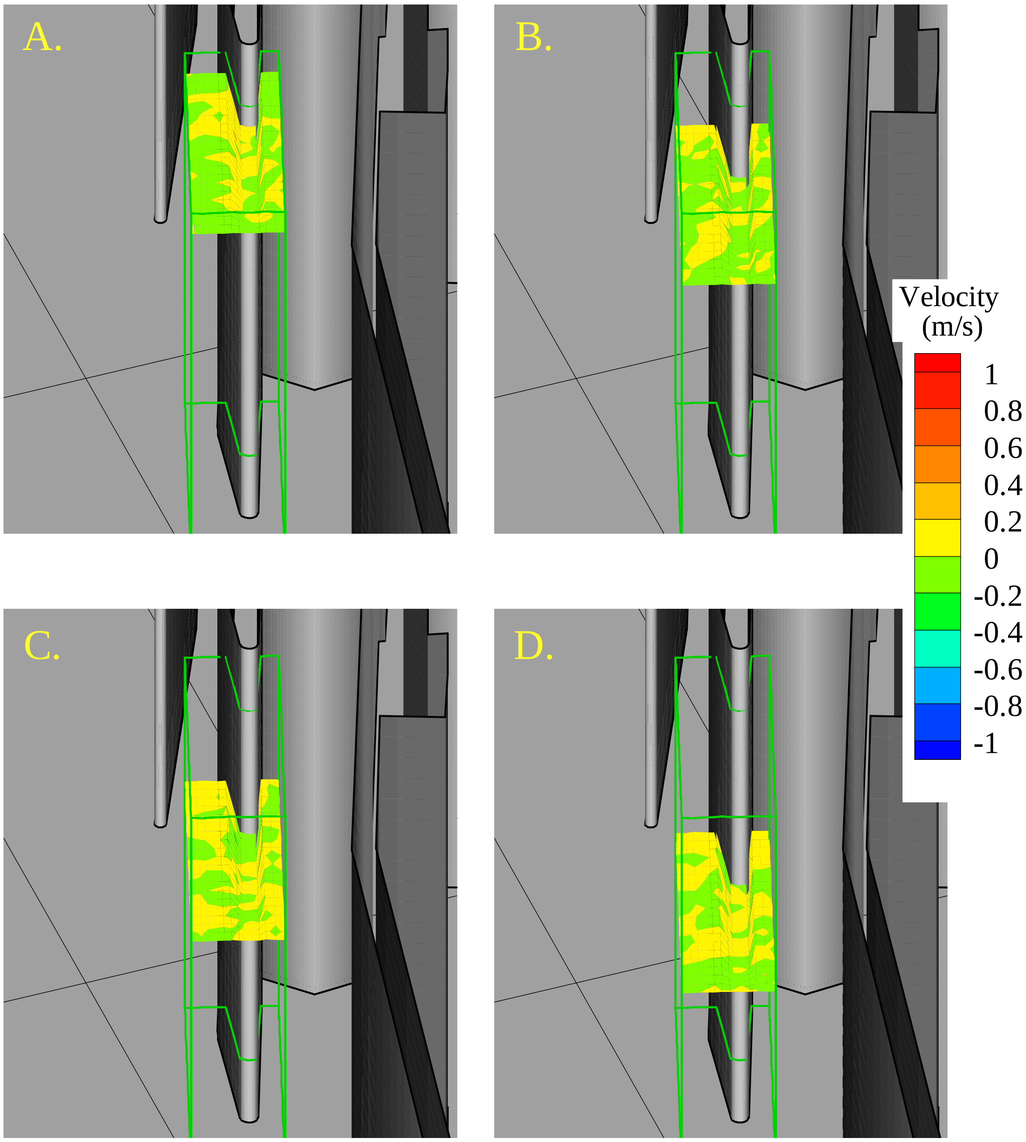

Figure 36. Contours of interpolated vertical water velocity by depth in the area of the saltwater drain. Depths displayed are 3 m (A), 4.6 m (B), 6.1 m (C) and 7.6 m (D). Data reflect conditions whereby only Flume 5B was operational.

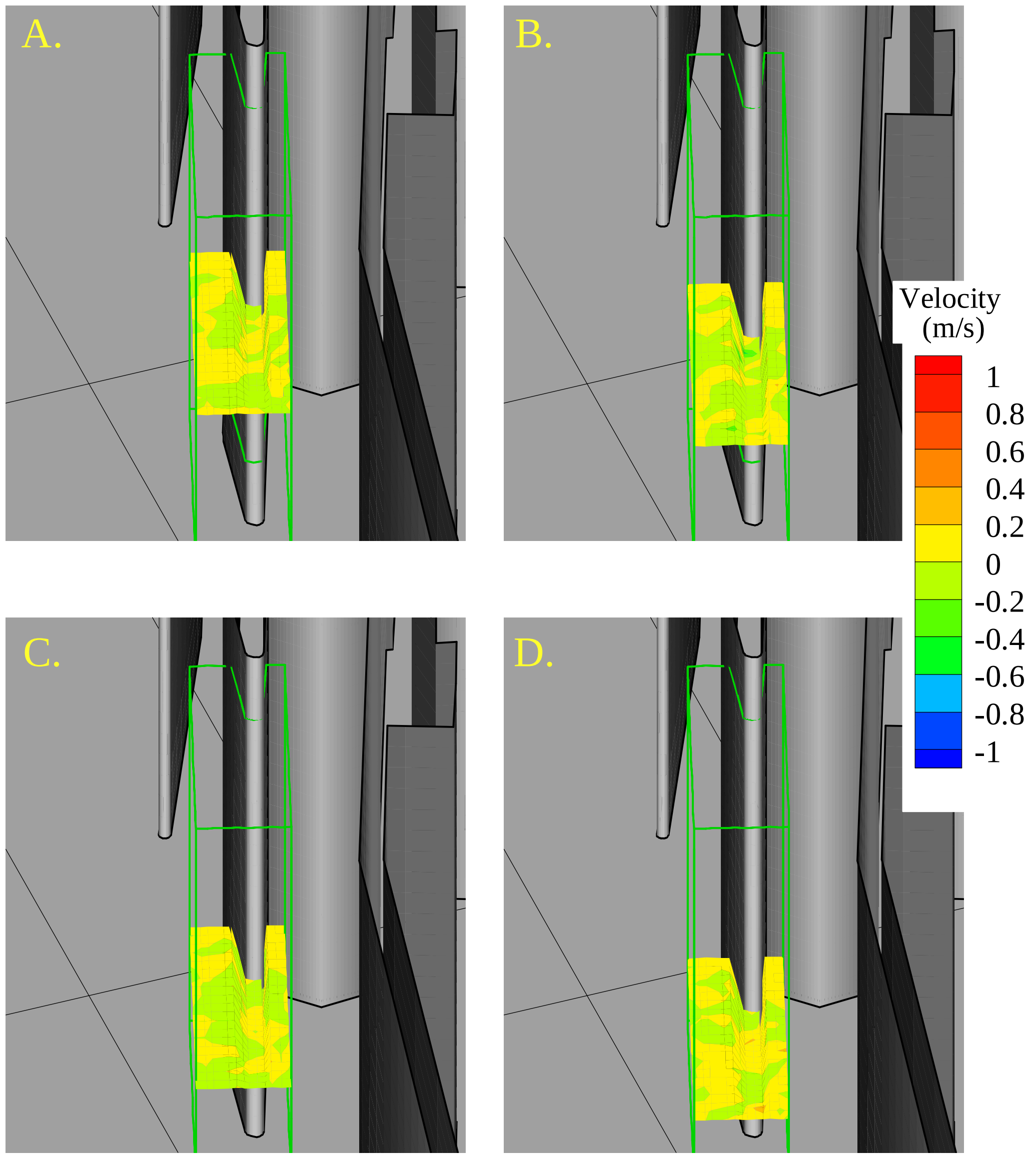

Figure 37. Contours of interpolated vertical water velocity by depth in the area of the saltwater drain. Depths displayed are 8.2 m (A), 9.1 m (B), 10.1 m (C) and 11 m (D). Data reflect conditions whereby only Flume 5B was operational.

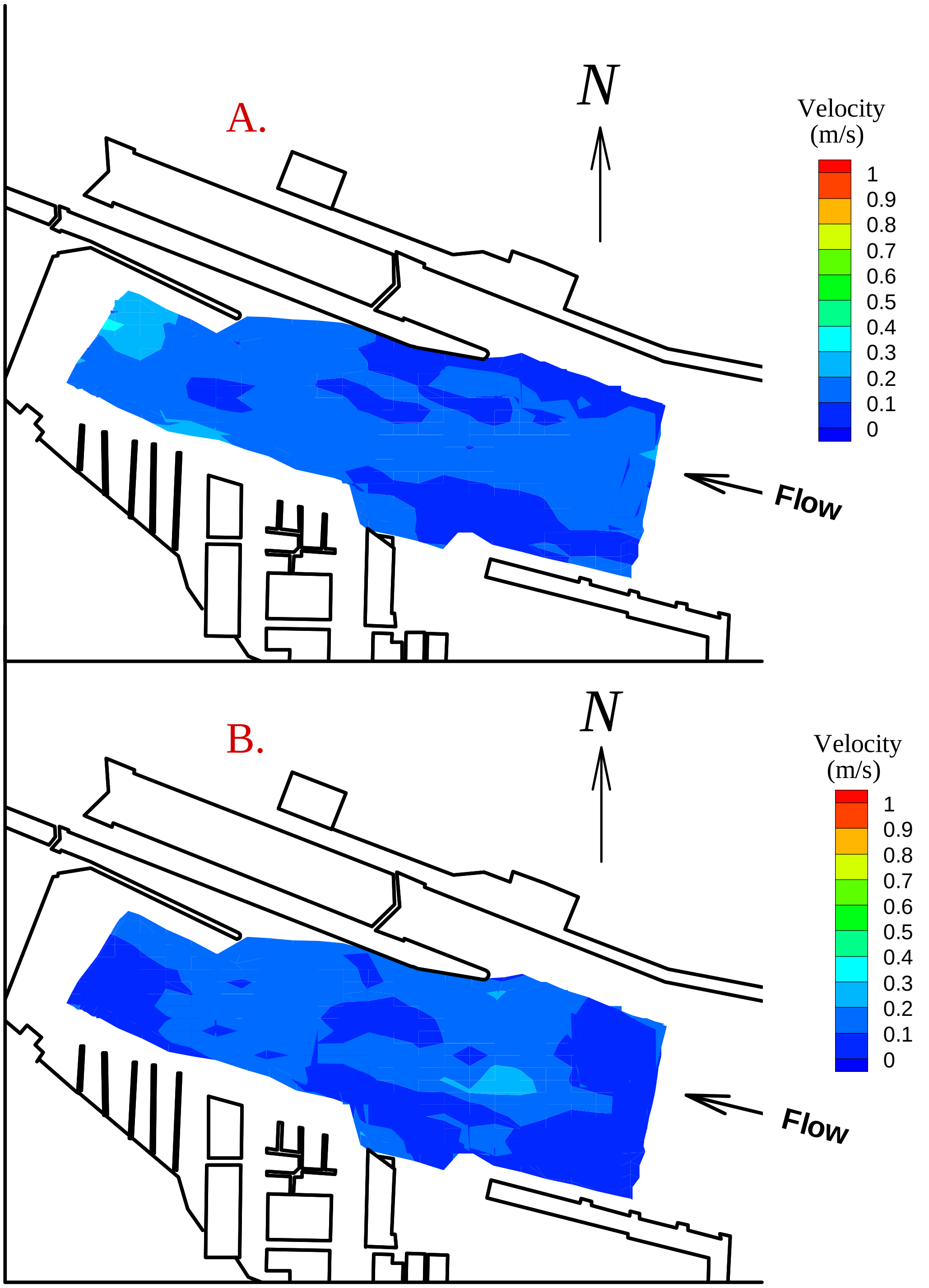

Figure 38. Plan view of interpolated water velocities at a depth of 1.2 meters in the spillway forebay. Flumes 4B, 5B, and 5C were operating in Panel A and only Flume 5B was operating in Panel B.

Discussion and Recommendations

Hydroacoustic Detectability

Improvements in detectability modeling yields hydroacoustic estimates that are quantitative and reliable relative indices to fish passage through structures. Our detectability modeling efforts resulted in high and consistent beam angles (Figure 8), reassuring us that the spatial expansion factors we used were not inappropriately overestimating entrainment through the filling culverts. The consistently high beam angles were likely primarily a function of the relatively slow speeds (< 0.4 m / sec; Table 1) of fish through hydroacoustic beams. Given the slow speeds, our sampling rate of 10 pings / sec was fast enough to obtain reliable passage estimates into the filling culverts.

Large Lock Culvert Passage

The large lock culverts did not appear to be a significant passage route for migrant juvenile salmon in 2000. Among days when we estimated fish passage over spillway flumes and through the filling culverts, culvert entrainment comprised a mere 2% of passage between the two routes (Figure 22). Even this very small proportion should be considered an overestimate of relative passage given that other passage routes, e.g., small lock filling culverts, small and large locks through open gates, were not sampled. Presumably, migrant juvenile salmon utilize all available passage routes through the Chittenden Locks Project to some extent.

By presenting culvert passage over time in terms of mean number of fish per fill per day (Figure 10), the effects of daily differences in lock operations (i.e., numbers and types of fills) are removed. Trends in culvert passage through the study period based on (Figure 9) revealed two primary modes of migration run timing, one in late June and one in mid to late July, and a secondary mode of smaller magnitude towards the end of May and into early June. Prior to the initial mode in late June and early July, estimated culvert entrainment was relatively uniform and was likely composed primarily of juvenile sockeye, coho, and chinook as indicated by species composition purse seine data collected at that time (Goetz et al. in prep). The mode in late June and early July coincides temporally with the arrival of the majority of PIT tagged juvenile chinook at the spillway flumes (DeVries 2000). The juvenile chinook were released from the University of Washington hatchery as part of a pilot study investigating smolt survival and passage through the Chittenden Locks Project. The purse seine species composition corroborates the PIT-tag data with juvenile chinook salmon making up 35% to 95% of the catch from June 13 to June 22. The secondary mode in late May and early June was primarily composed of juvenile pink salmon. On May 24, 25, 31, and June 1, pink salmon made up 74% to 100% of the juvenile salmon catch in the lock chamber.

Unfortunately, we were unable to acquire video images of culvert entrainment due to gear failure. The utility of such images in this environment is that it provides fish behavioral data as well as the potential for species composition data. Since hydroacoustic sampling does not furnish information on species composition, video data can be used to infer species composition of acoustic estimates of fish passage. We recommend the development of this tandem approach to monitoring fish passage in future entrainment investigation at the Locks.

Differences in Entrainment Between Upper and Full Locks

As expected, full chamber fill events entrained greater numbers of fish than did upper chamber fills (Figure 11). This is no surprise given that almost twice the amount of water is required to fill the full lock versus the upper lock. Presumably, the area of influence near the large lock entranceway during full lock fills is larger and extends up into the Lake Washington Ship Canal to a greater extent than during an upper lock. We therefore recommend that full lockages be used only when absolutely necessary to minimize potential fish entrainment. One could argue that there would be no real difference between one full lock fill and two upper lock fills in terms of fish entrainment. However, we speculate that fewer fish would be available over the course of two upper fills because during the period between fills, migrant fish would have the opportunity to search for and discover the friendlier spillway flume passage route.

Additionally, we recommend that upper lock fills be used with preference over lower lock fills whenever feasible because we suspect that the latter would entrain more fish than the former. We did not sample for lower lock fill entrainment, as the lower lock is filled via 22 portals on the floor along the wall of the upper chamber, sampling would have required the use of several hydroacoustic systems and consequently was outside the scope of this project. Nonetheless, we assume that lower lock fills would result in increased entrainment of juvenile salmon for two reasons. First, lower lock fills would draw water (and presumably fish) inside the upper lock chamber toward the middle miter gates. Fish that are drawn into the upper chamber but not entrained are left in a vulnerable position. They would be available for entrainment in the next lower lock fill unless they swam upstream around the south pier of the large lock to find the spillway flume passage route. Second, assuming the skewed vertical distribution of fish toward lower portions of the water column observed at the culvert entrances (Figures 16 and 17) are similar to distributions in the large lock, and given the location of the filling portals on the floor spread along the entire length of the upper chamber walls, the area whereby fish would be at risk of entrainment would be spread out to a larger extent than during an upper fill, likely resulting in greater entrainment.

Differences in Entrainment Between Filling Culverts

The differences in daily entrainment estimates between the north and south filling culverts (Figure 12) were rather intriguing. We found the north culvert passed significantly more fish after 1 July ($P=0.039$), than did the south culvert, likely the result of a slight preference for migrating along the shallower Lake Washington Ship Canal margin over migration down the deeper channel. The temporal nature of the differences between north and south culvert passage, suggest a species-specific migratory preference. Or this difference in entrainment among the two culverts may result from a portion of the migrating schools of fish being funneled off by the pier between the large and small locks, leaving greater numbers of fish near the north culvert relative to the south culvert. Generally, velocities were higher along the north wall relative to the south wall based on two of the three transect data plots (Figures 27 and 28), which may contribute to the difference in passage between the two culverts.

Effects of Fill Rate

Small sample size, coupled with the inherent confounding effects of run timing on comparing entrainment rates across fill types, precluded a determination of effects of fill rate on entrainment. The purpose being a determination of which fill rates (among graduated, intermediate, and slow-continuous valve opening procedures) result in minimal relative entrainment through the filling culverts. The assumption being that the slower the fill rate, the fewer fish entrained. Unfortunately, we were only able to schedule a small number of slow-continuous and graduated fill types during the period of hydroacoustic assessment of fish entrainment (n=13). We recommend a future study design for examining the effects of variable fill rates on fish entrainment based on the following: (1) increase the sample size to 30 fills for each of the three fill types; (2) select 10 days during the juvenile salmonid migration period in which the experiment would be conducted (minimizes daily run timing effects), with each day consisting of three blocks with each block comprised of randomly selected fills of each type; (3) remove hourly run timing effects by normalizing entrainment estimates by block with flume passage counts during time periods paired with the blocks; and (4) perform analysis of variance to detect differences in entrainment among fill types and interaction effects of blocks and days.

Diel Entrainment

Entrainment over the diel cycle in 2000 (Figure 13) revealed that the highest entrainment rates occurred during periods of darkness for both upper and full chamber fills, contradicting previous studies conducted in the entranceway to the large lock that reported lower fish abundance at night versus day in 1996 (Dillon and Goetz 1999) and in 1998 (Johnson et al. 2000). Additionally, other studies have shown negligible fish passage over the Chittenden Locks spillway at night versus day in 1995 (Goetz et al. 1999) and in 2000 (DeVries 2000). Why culvert entrainment estimates were higher during nighttime hours in 2000 while all other research efforts show lower relative fish abundance near the culverts, entrainment through the culverts and passage over the spillway at night is unclear.

What may be most interesting regarding the diel entrainment patterns during upper and full chamber fills is that the patterns are different. Although both conditions show increases in entrainment at night relative to daytime hours, entrainment increases by a factor of 3.3 during full chamber fills, and by a factor of only 1.5 during upper chamber fills. Therefore, more than twice as many fish are entrained at night than are during the day during full chamber fills relative to night and day differences in fish entrainment during upper chamber fills. We speculate that this unusual result is likely a consequence of two factors: (1) the larger size and further upstream extent of the area influenced by full chamber fills relative to upper chamber fills; and (2) nighttime fish distributions in the vicinity of the large lock entranceway. Based on mobile hydroacoustic surveys in 1998, large schools of fish were found to aggregate near the large lock entranceway at depths at or near the bottom at night (Dawson and Goetz in prep.). These near-bottom dwelling aggregations were consistently observed in the same general areas during nightly surveys, and they appeared to be stationary. Perhaps because of the greater extent of the area influenced, full chamber fills had the effect of entraining a portion of the fish aggregations. In contrast, the area of influence during upper chamber fills was not as large and did not extend as far upstream, so those fish aggregations likely were not available for entrainment during upper chamber fills.

Target Strength

Analysis of fish target strengths is a critical component of hydroacoustic-based fish passage investigations. Fish lengths can be approximated based on mean fish target strengths using regression equations derived by Love (1971, 1977), and mean target strength is a necessary and important input parameter in hydroacoustic detectability modeling. Target strength distribution analysis among entrained and non-entrained fish through the study period revealed that smaller fish were entrained at higher rates than were larger fish (Figure 14). This result was expected assuming that larger fish have greater swimming capacity and could avoid entraining flows to a greater extent than can smaller fish. Higher entrainment with smaller fish relative to larger fish was also observed temporally (Figure 15), which suggests that each population of migrating juvenile salmon may be size-variable, and that larger fish of each population are successfully avoiding entrainment. Temporal target strength distributions of entrained fish also shows a steady increase in fish size from 19 May to 28 June, then a decline in size to 18 July and another increase into the beginning of August. These shifts in mean target strengths over time reflect size variability among different migrant populations of juvenile salmon. Species composition data from purse seining efforts in the large lock in 2000 was highly variable and does not necessarily parallel the target strength data. Predominate species prior to May 19 were larger coho and sockeye salmon smolts, from May 23 to June 1 smaller pink and chum salmon fry predominated, and from Jun 6 to June 22, chinook and pink salmon were predominate (Goetz et al. in prep).

Vertical Distributions

Consistent patterns from year to year of vertical distributions of fish prior to fill events skewed towards the floor of the lock entrance underscores the necessity for redistribution of fish as a means of minimizing culvert entrainment at the Locks. The majority of fish in front of the filling culverts prior to fill events were distributed within four m of the large lock entranceway floor in 2000 (Figure 16), depths that coincide with the elevation of the culvert openings. Consequently, a large proportion of fish present in front of the filling culverts is vulnerable to culvert entrainment during fill events. Vertical distribution patterns observed prior to fill events in 2000 were similar to those observed during both day and night periods in front of the north filling culvert in 1998 (Johnson et al. 2000). Johnson et al. (2000) demonstrated the efficacy of strobe lights for redistributing fish and reducing entrainment in a pilot study at the Locks in 1998, and we recommend further application and evaluation of strobe lights and other behavioral technologies to continue improving fish passage at the Locks. Vertical distributions during daytime fill events were also similar across years, as a slight proportion of fish shifted from deeper strata to shallower strata relative distributions before fill events. However, nighttime fill event distributions were not similar between years. The vertical distribution pattern during nighttime fill events in 1998 showed the majority of fish near the surface and proportionally very few at the depth of the culvert. In 2000, distributions during nighttime fill events were much like those of daytime fill events. The likely reason for this difference is unclear, although nighttime densities of fish in 1998 were observed to be smaller than daytime densities that same year by a factor of 4.6 (Johnson et al. 2000).

Flume Passage

The development of sampling techniques for estimating fish passage over the flumes in 2000 was an evolving process. Although overhead video sampling was shown to be a fairly effective method in prior investigations of fish passage over a prototype smolt flume in 1997 (Johnson 1997) and 1998 (Johnson 1999, 2000), we found that video sampling was not feasible in 2000. Higher flow velocities and greater degrees of turbulence in the new flumes relative to the prototype, as well as problems associated with glare and weather conditions, confounded our attempts of video imaging smolt passage at the flumes in 2000. Instead of video, we relied on visual observation to quantify smolt passage over the spillway flumes, and this sampling technique proved to be beneficial for a number of reasons. First, weather conditions such as rain or intense sun glare did not hinder observers' ability to view smolt passing out of the bottom of the flumes and into the water below the spillway. The human eye can adapt to changes in light levels more quickly and efficiently than can the cameras. Second, visual counting provides equal sampling effectiveness among all flumes, whereas effectiveness of video would be specific to each flume since angle of the sun, shadows and available light levels would differ among the flumes. Third, and perhaps most importantly, visual counts provide passage estimates in real time, i.e., there is no processing involved (unlike video which involves viewing and reviewing of the tapes). Real time counts are highly valuable because they can be used in decision-making processes regarding Project operation. For instance, if scheduled maintenance requires the shutdown of the flumes and real time counts indicate high flume passage rates, maintenance could perhaps be delayed until flume passage rates decrease.

Flume passage in 2000 was comparable to passage over the prototype flume in 1997 (Johnson 1997) and 1998 (Johnson 1999) in terms of general run timing. In all years, the majority of the passage occurred prior to 6 June, although it should be noted that sampling effort and timing differed among years and prior to 2000, flume counts were based on video sampling. The diel passage pattern in 2000 was different than in previous years as passage decreased steadily through the morning hours (Figure 22) and after a slight increase at noon, steadily declined again through the afternoon before peaking at 1700. Diel passage of most species of PIT tagged fish in 2000 (DeVries 2000) resembled the patterns we observed based on visual counting. In 1997, passage was steady through the morning hours with a major peak at 1800 (Johnson 1997). In 1998, passage initially peaked at 0800, declined in later morning hours and increased rapidly in the early afternoon to a peak at 1400 (Johnson 1999). It is unclear why diel flume passage appears to vary from year to year, but again we emphasize that differences in sampling effort and technique across years confound these comparisons.

Visual sampling efforts for monitoring flume passage in 2000, in terms of which hours, and the number of hours sampled, differed on a daily basis (Table 3). Thus, estimates of run timing of flume passage should be viewed with attention paid to the confidence limits around the passage estimates (Figure 20). Days with fewer relative hours sampled yield less reliable passage estimates. We recommend a more consistent approach to sampling flume passage in future years, with emphasis on equal sampling effort among all days sampled.

Higher proportions of fish passed over Flume 5B relative to all other flumes through the study period, and Flume 5C passed increasingly greater proportions through the course of the study (Figure 23, Table 4). These same results were observed for PIT tagged fish, especially juvenile chinook (DeVries 2000). These data, coupled with diel passage patterns of PIT tagged fish (DeVries 2000) have implications regarding flume operations in low water years. If water management of Lake Washington dictates decreased discharge through the Locks, we suggest the following: 1) shut all flumes off at 2300 and open them back up at 0500 the next morning each day; 2) if water conservation necessitates closure of flumes during the day, Flume 4A should be closed first, followed by Flume 4B then Flume 5C; 3) if further conservation measures are required, then Flume 5B should be closed at 1700 each night and reopened again 0600 each morning.

Relative Flume and Culvert Passage

During periods when more than one flume was open, culvert passage comprised only 1% of total passage between the two routes (Figure 24). This data clearly indicates that the smolt passage flumes were incredibly effective for attracting and passing juvenile salmonids in 2000. Although not apparent based on velocity mapping in the spillway forebay (Figure 38), we assume that the passage flumes create a near-surface attraction flow that extends upstream beyond the entrance to the large lock. Migrating smolt may well detect the surface flow upstream of the large lock entrance and this likely influences their through-Project passage route. We recommend more intensive velocity measurement of the near surface flows associated with flume operation in order to characterize the magnitude and extent of the flume-generated flow net.

Flow Velocity Characterization

Eliminating sources of bias was a priority during data collection. By measuring water velocities at a single point throughout an entire fill we were able to eliminate boat movement as a source of error. The changing velocities seen at our sample locations illustrate the necessity of such a strategy. We were unable, however, to eliminate other sources of error. The influence of the tidal height on the volume, the velocity, and the duration of fill events is considerable at the Locks. This can be nearly eliminated as a source of error if all samples are taken at a narrow range of tidal heights, but this was not possible during the summer of 2000 due to the short window of sampling opportunity. We felt confident that we would still be able to detect general patterns of water velocity even with a wider than ideal range of tide values during data collection.

Another source of error, one that was not anticipated, involved differences in the operation of the lock filling valves. Since the valves are not automated it would be difficult under ideal conditions to get good replications of separate fill events. It becomes more difficult when the locks are busy, as they were the days that we sampled. The samples from the center transect have velocity patterns that are very different than samples from other locations. It appears that the valves were either opened too quickly (the sample from the north point) or too slowly (the sample from the center point) during these fill events. It is not apparent why the sample from the south point of the center transect differed from the samples from the east and west transects.

The water velocity patterns we observed in the east and west transects are similar and probably are good examples of the flow patterns that occur in the large lock entrance during intermediate fill events. The operation of the fill valve appears to have been similar for these samples and the bias introduced by tidal fluctuations does not seem to have been great enough to invalidate comparisons between the samples.

The general velocity pattern seen in the valid samples from the large lock entrance, characterized by fairly slow currents for the first two-thirds of a fill followed by a large increase during the last one-third of the fill, was very similar to the velocity pattern seen at the culvert opening. The most noticeable difference between the velocities from the culvert opening and those from the large lock entrance was the magnitude of the velocities. Maximum velocities in the culvert opening were twice those in the large lock opening.

The high water velocities detected at the culvert openings appear to have been very localized. The samples from the large lock entrance that were closest to the culvert openings were about 7.6 meters away from the culverts, yet water velocities from those points were more similar to velocities from the east transect than they were to those detected at the culvert opening. The apparent consistency of the timing and magnitude of water velocities in the large lock entrance suggests that flow during a fill event is similar throughout the large lock entrance except for the area just outside of the culvert opening. This would be expected given that velocity decreases in proportion to the inverse of the cube of distance from the entrance.

The highest velocities observed while sampling the area near the saltwater drain occurred deep in the water column (Figure 31), likely the influence of the drain itself. The influence of the drain was most apparent at a depth of 11 meters, but it was also evident at 10 meters. Relatively high velocities were also detected in the upper water column. It is unclear whether these velocities were naturally occurring and were the result of spillway flume operations or they may have been caused by turbulence introduced by boat traffic. Boat traffic, however, was not particularly heavy during the sampling of the saltwater drain area.

The attraction flows that smolts encounter as they move into the west end of the spillway basin vary by both the amount of water going through the smolt flumes and by the spill discharge. Spill discharge was zero during our data collection so velocities in the spillway basin were minimized. The effect of flume discharge alone on the water velocities at the opening of the large lock entrance was either non-existent, very low, or concentrated in the top few feet of the water column. The ability of the flumes to pass high concentrations of fish is dependent on the smolts either slowly moving downstream with the bulk flow until they reach the higher velocities leading to the flume, or milling around the spillway basin until they encounter attractive flows to the flumes. Under low flow conditions, such as those we sampled, spillway basin residence time may be decreased, and flume passage may be increased using behavioral guidance techniques aimed at increasing smolt passage rates through the relatively slack water spillway basin. We recommend the development and evaluation of turbulence induction as a means to direct flow and increase flume passage rates during low flow conditions at the Locks.

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